JUN 29 1981

Y3.T25:2F39

COMPLETED ORIGINAL not mailed
53 7-8-81

FERRORESONANCE TESTS ON THE 500-kV POTENTIAL TRANSFORMERS AT WATTS BAR NUCLEAR PLANT

J. R. Boyle

C. L. Ballentine

B. R. Farris

TENNESSEE VALLEY AUTHORITY

CHATTANOOGA, TENNESSEE

BEST DOCUMENT AVAILABLE

A DISCUSSION OF FERRORESONANCE

It is not the purpose of this discussion to make a complete analysis of ferroresonance but to present a simplified one which will possibly assist in the understanding of this phenomina.

The simplist form of ferroresonance can be represented by the circuit in Figure 1.

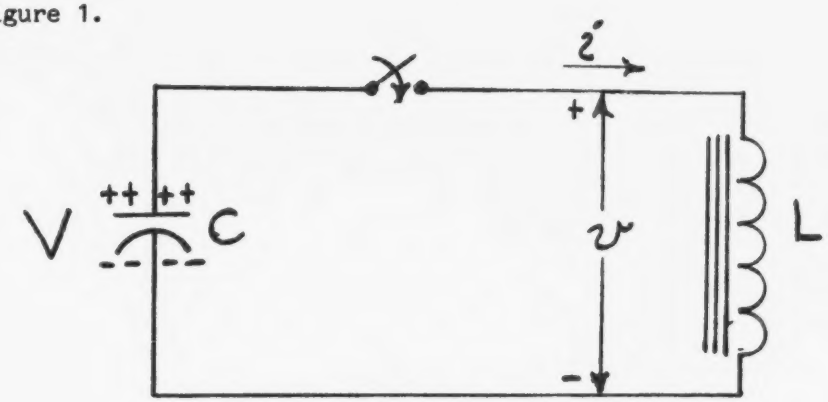


Figure 1

A Simple Ferroresonant Circuit

In Figure 1, a capacitor charged to some voltage, V, is switched on to a saturable inductance. This will cause sinusoidal voltage and current to flow as follows:

$$v = V \cos\left(\sqrt{\frac{1}{LC}}\, t\right)$$

$$i = V\sqrt{\frac{C}{L}} \cos\left(\sqrt{\frac{1}{LC}}\, t - 90^\circ\right)$$

BEST DOCUMENT AVAILABLE

These quantities can be represented with phasors as shown in Figure 2.

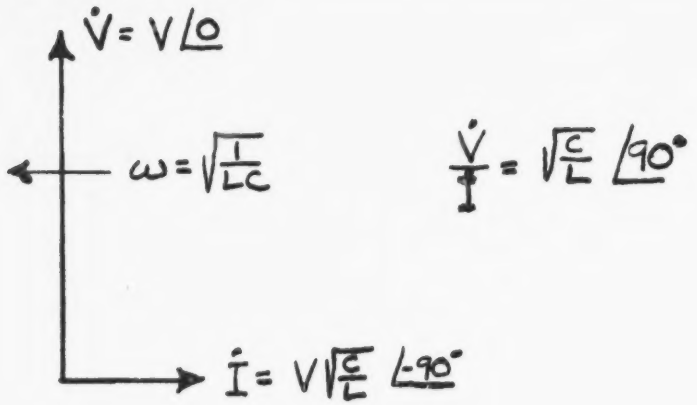


Figure 2

Initial Conditions

In Figure 2, the vertical axis is taken as reference and the instantaneous values are the projections on this axis. The voltage and current phasors will be as shown at time zero and will rotate as indicated until the current reaches the saturation level as shown in Figure 3.

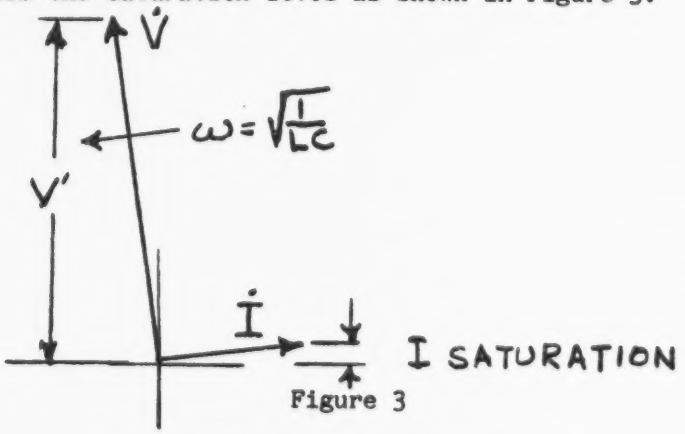


Figure 3

Conditions When Reactor Saturates

BEST DOCUMENT AVAILABLE

When the reactor saturates, its inductance will decrease very much and the new phasor diagram will become as shown in Figure 4.

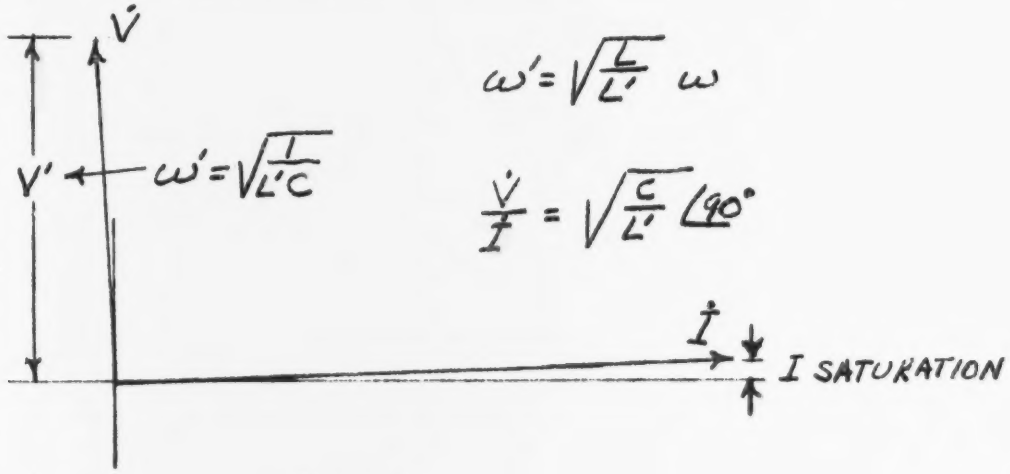


Figure 4

Conditions Immediately After Saturation

After the reactor saturates, the frequency will increase and the ratio of V/I will decrease. The instantaneous values of V and I will not change, however, and this will cause a slight phase shift in the phasors. The phasors in Figure 4 will then rotate about 180 degrees at the higher frequency until the reactor unsaturates as shown in Figure 5.

Figure 5

Conditions When Reactor Starts to Unsaturate

BEST DOCUMENT AVAILABLE

At this time, the voltage and current will return to the original conditions as shown in Figure 6.

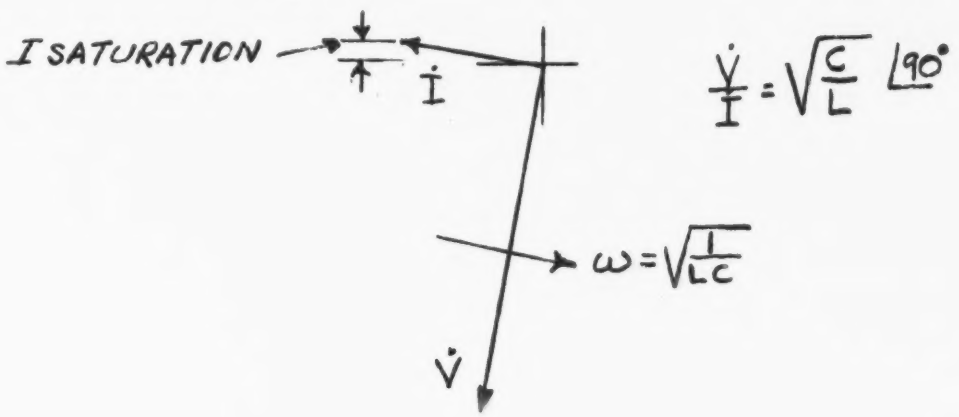


Figure 6

Conditions When Reactor Unsaturates

The voltage and current will continue to rotate at the lower frequency until the reactor saturates again. Again, the instantaneous values do not change and there is a slight phase shift in the phasors.

It is noted that while the reactor is saturated, there is almost one-half cycle of current and voltage at the higher frequency producing a pulse of current and a rapid change in voltage. This phenomina will continue indefinitely since there is no resistance in the circuit.

The above conditions can be represented graphically with perhaps a little more clarity.

BEST DOCUMENT AVAILABLE

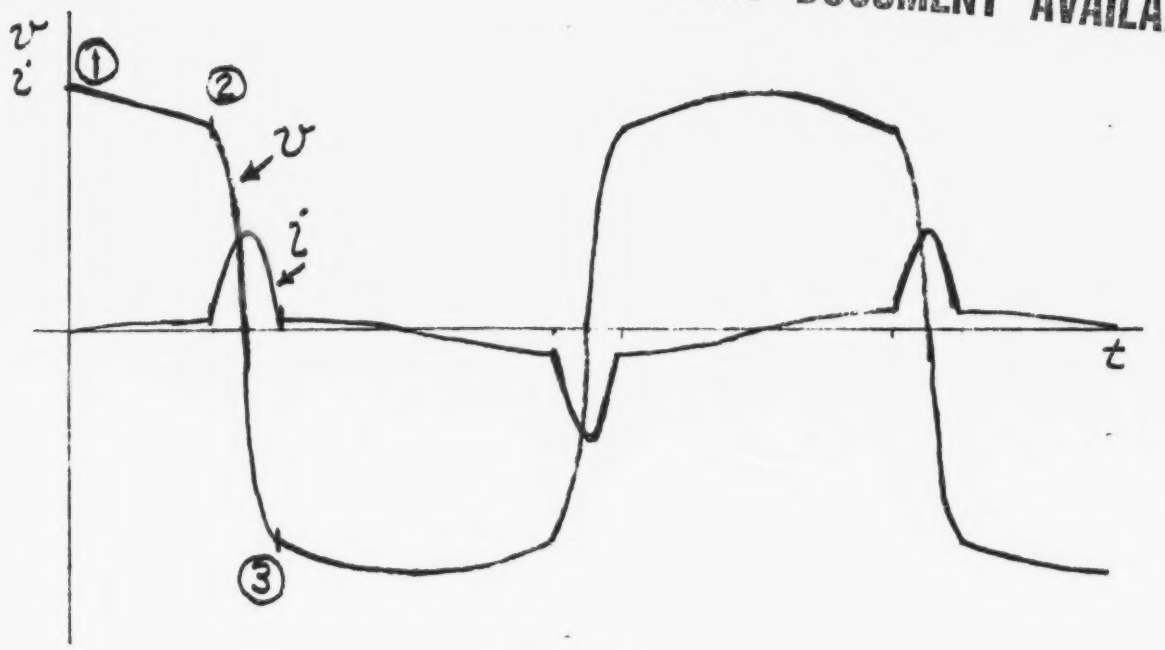


Figure 7

Graphical Representation of Ferroresonance

Point 1 in Figure 7 indicates the initial condition and corresponds to Figure 2; point 2 indicates where the reactor saturates and corresponds to Figures 3 and 4; and point 3 indicates where the reactor "unsaturates" and corresponds to Figures 5 and 6. Between points 2 and 3, there is about one-half cycle of voltage and current at the higher frequency while the reactor is saturated. It is noted that the current lags the voltage ninety degrees since they are applied to the reactor.

If resistance is added to the circuit, the oscillations will be attenuated and finally decay the zero. If an alternating voltage source is applied, the circuit is further complicated by two steady state conditions, one in the unsaturated state and one in the saturated state. It is likely that the two conditions are 180 degrees out of phase as shown in Figure 8.

BEST DOCUMENT AVAILABLE

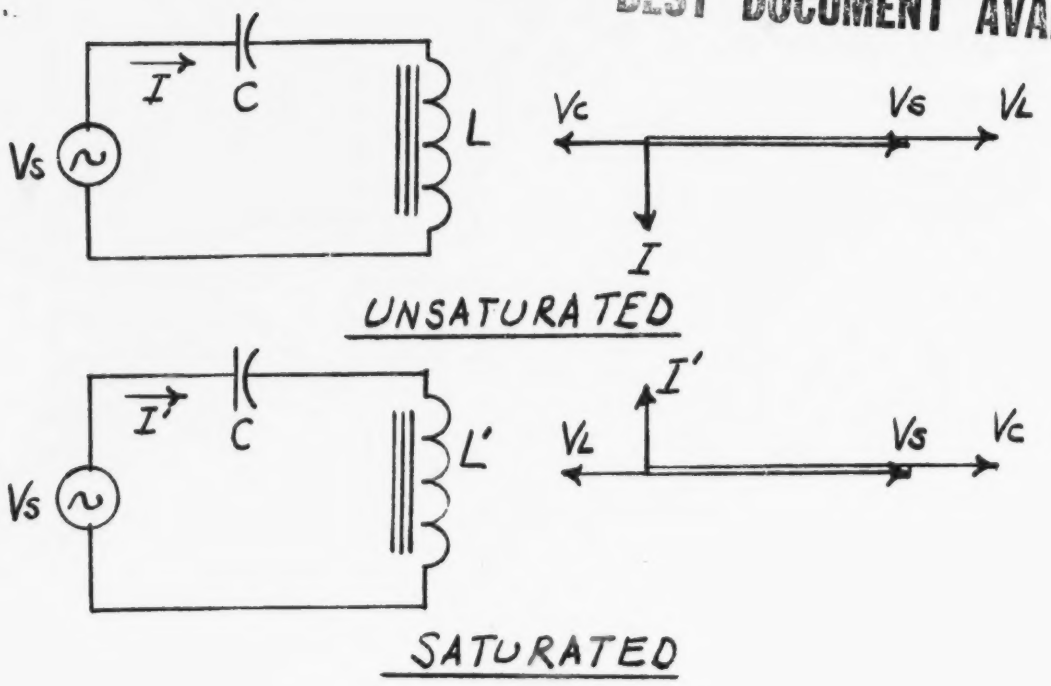


Figure 8

Possible Steady State Conditions

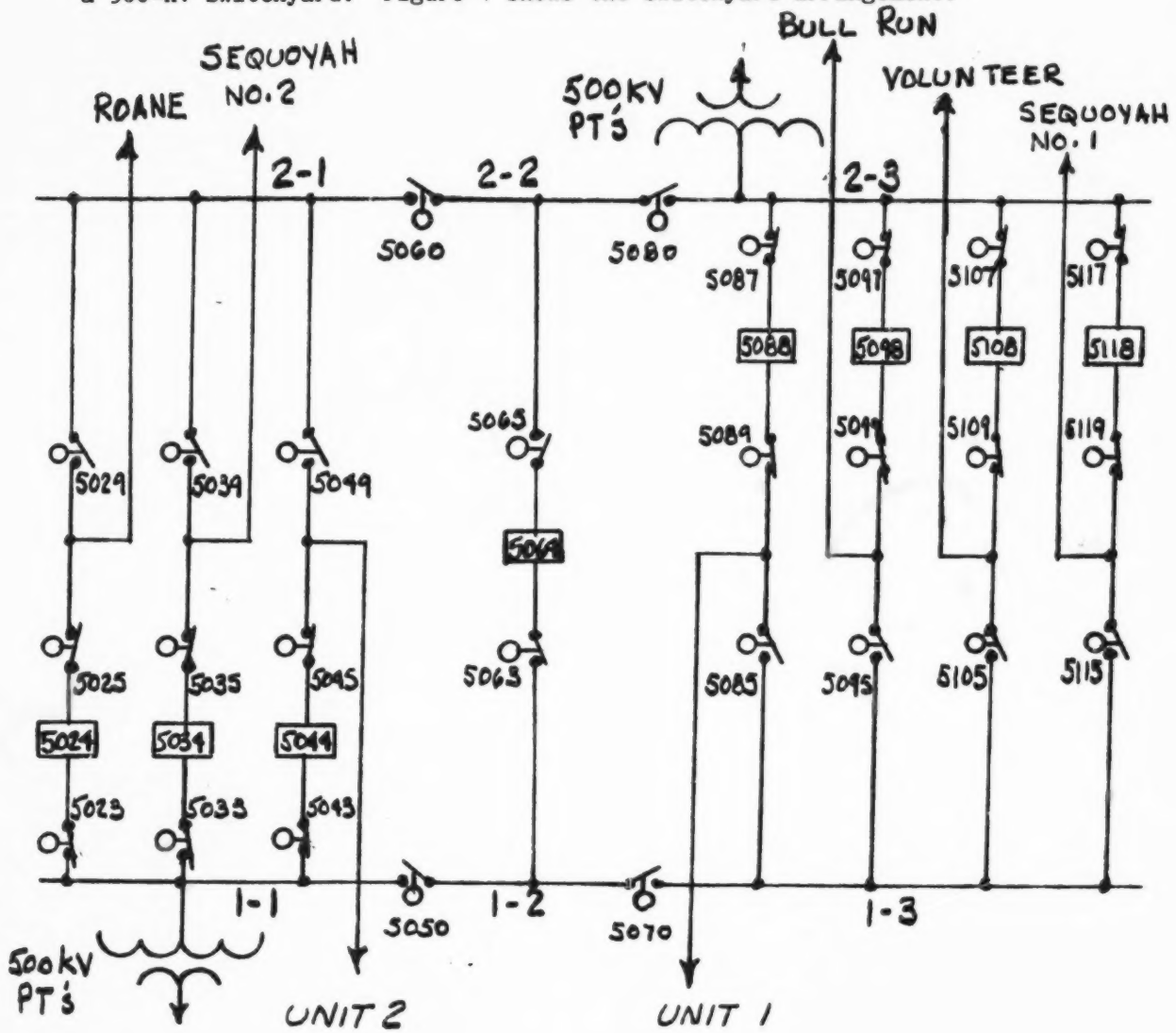
When the reactor saturates and unsaturates, drastic changes will be required in the voltages and currents. These changes will occur at the natural frequency of the circuit. The changes that are most noticeable will be in the saturated state where the high current spikes and voltage jumps occur.

It is evident that the ferroresonant problem is so complex that the best way to analyze even the simplist circuit is by actual measurements or with a computer. The following write-up discusses pt failures on December 8, 1979, and the results of actual measurements on a section of the 500-kV bus at TVA's Watts Bar Nuclear Plant and computer studies to substantiate the results of the measurements.

BEST DOCUMENT AVAILABLE

THE FERRORESONANT CONDITION AT WATTS BAR N.P.

Watts Bar Nuclear Plant is now under construction and is being operated as a 500-kV switchyard. Figure 1 shows the switchyard arrangement.



Watts Bar Nuclear Plant

Figure 1

The switchyard is split with MOD's 5060, 5080, 5050, and 5070 normally open since it is planned to operate separately with one unit tied to each switchyard.

Prior to December 8, 1979, the 500-kV bus 1, section 1, was out of service for maintenance purposes. The Roan-Sequoyah No. 2 Line was tied through on bus 2, section 1, through mod's 5029 and 5039. In preparation for returning bus 1, section 1, to service the following switching was performed.

(1) Time: 1627

Close motor operated disconnects (mod's) 5023, 5025, 5033, and 5035.

(2) Time: 1628:41

Close power circuit breaker (pcb) 5024. Normal voltage was observed on bus 1, section 1, indicating meters.

(3) Time: 1628:56

Open pcb 5024. The bus 1, section 1, indicating meter read greater than 600-kV (off-scale). This condition existed for 21 minutes while all phases of pcb's 5024 and 5034 were checked open by the operators. (See oscillograph No. 1.)

(4) Time: 1650

The indicating meter dropped to 400 kV. MOD's 5023 and 5025 were opened. The indicating meter dropped to zero volts. (See oscillograph No. 2 and No. 3)

(5) Time: 1651

Close pcb 5034. This resulted in an explosion and fire involving the A and B phase potential transformers (pt's). PCB 5034 tripped by relay action in 2.5 cycles. (See oscillograph No. 4)

The A and B phase pt's were completely destroyed. An adjacent station service transformer and 6.9-kV bus housing were also damaged.

The station oscillograph revealed that a ferroresonant condition existed on the pt's when the 500-kV bus was "de-energized" by pcb 5024 (see oscillograph No. 1). This condition subsided about the time the indicating voltmeter reading reduced from "off scale" to 400 kV (see oscillograph No. 2). This may indicate that the damage to the pt's occurred at this time. There was not enough current through the capacitance of the open pcb's 5024 and 5034 to destroy the pt's until pcb 5034 was closed (see oscillograph No. 4).

The 500-kV pt's are GE, type EW-1800Y, pri. volts = 300,000; ratio = 2500/4500-1, 10-kVA, 55°C, BIL = 1800-kV, Insulation Class 400, dual secondaries each rated 7.5 kVA.

The 500-kV pcb's are Brown Boveri, type DLF 550 PC6, 500-kV, 3000-amperes, air blast circuit breaker, 40 kA. Six breaks per phase with 3000 pF capacitor across each break, 500 pf per phase.

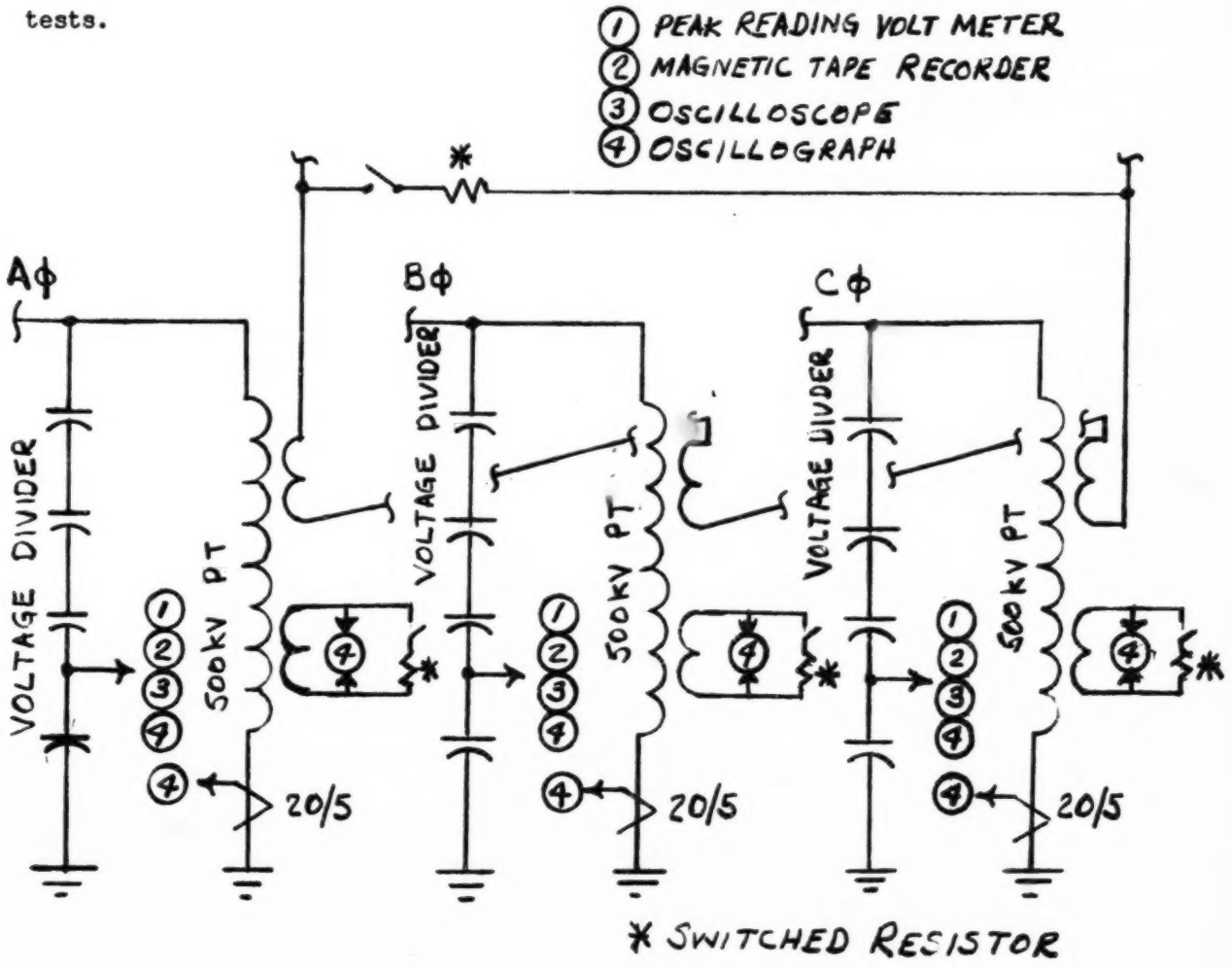
It was first thought that the pt's had failed due to the thermal effects of ferroresonance due to high current in the pt primary. Inspection of a pt which may have been exposed to ferroresonance did not reveal any visible thermal damage but some small punctures in the insulation were found, indicating damage due to overvoltage.

TESTS

On November 5, 1980, tests were made at Watts Bar to more accurately determine the voltage and currents that exist on the 500-kV pt's during ferroresonance. Three good pt's were available on bus 2, section 3, and pcb's 5098, 5118, and 5064 were also available. The Bull Run-Sequoyah No. 1 500-kV Lines were tied through on bus 1, section 3, through mod's 5095 and 5115 (see figure 1). As previously mentioned, there was some concern about making the tests since there was evidence that the pt's had failed due to overvoltage during ferroresonance. It was decided, however, to make the tests on the basis that since the ferroresonant condition exists, we need to know how severe it is and how to prevent it. We also concluded that damage caused by ferroresonance was a function of time. Therefore, the duration of each test was kept to a minimum.

BEST DOCUMENT AVAILABLE

To initiate ferroresonance, the 500-kV bus would be energized and then "de-energized" while being fed through one, two, or three open pcb's. The quantities measured would be primary voltage, primary current, and secondary voltage on the pt's. The primary voltage would be measured by special 20 picofarad capacitance voltage dividers on the bus. This capacitance was small enough to not influence the test results. Figure 2 illustrates the quantities measured and the instrumentation used for the tests.



Ferroresonance Tests

Figure 2

BEST DOCUMENT AVAILABLE

If ferroresonance was started, an attempt to stop it would be made by switching resistive burdens across the pt secondaries and then across the broken delta of the secondaries. If the resistive burdens did not stop ferroresonance, then the mod's would be opened.

Following is a description of the tests and test results.

Test No. 1 - Close MOD's 5099 and 5097. Energize bus 2, section 3, through open pcb 5098.

Results

No ferroresonance, bus voltage as follows:

AØ = 50.7 kV rms
BØ = 45.0 kV rms
CØ = 49.0 kV rms

Test No. 2 - Close pcb 5098 energizing bus 2, section 3; then open 5098.

Results

No overvoltages
Bus voltage same as in Test 1.

Test No. 3 - Close MOD's 5097, 5099, 5117, and 5119. Close pcb 5098 energizing bus 2, section 3; then open pcb 5098. (See oscillograph No. 5A)

BEST DOCUMENT AVAILABLE

Results

B-phase went into ferroresonance in about 0.4 second (see oscillograph No. 5B) and A-phase in about 0.55 second. (See oscillograph No. 5C) C-phase did not go into ferroresonance. After it was determined that the pt's were in ferroresonance, the following burdens were switched in sequentially. (1) Across the broken delta: 1.5 ohms, 0.6 ohms. (2) Across each pt 67-volt secondary: 5.2 ohms, 2.5 ohms, 1.2 ohms. These burdens did not take the pt's out of ferroresonance.

The following data was taken from the oscillograph.

Maximum A-phase voltage = 800-kV peak

Maximum B-phase voltage = 697-kV peak

Typical A-phase voltage = 720-kV peak

Typical B-phase voltage = 656-kV peak

Typical A-phase amperes = 4.2-ampere peak

Typical B-phase amperes = 4.2-apere peak

The A-phase and B-phase amperes are the currents in the primaries of the pt's. The wave shape of the currents appear to be one-half cycle of a sinusoidal wave about 1.67 ms wide which indicates a frequency of 0.5 cycle/1.67 ms = 300 Hz. The rms value of the current should be 4.2 x 0.707 (1.67/8.33) exp. 1/2 = 1.33 amperes.

BEST DOCUMENT AVAILABLE

Test No. 4 - Repeat Test No. 3

Results

All three phases go into ferroresonance. (See oscillograph No. 6) Again restive burdens were switched onto the pt secondaries as in Test No. 3, and the ferroresonance was not stopped. The following data was taken from the oscillograph.

Typical A-phase voltage = 590-kV peak

Typical B-phase voltage = 629-kV peak

Typical C-phase voltage = 522-kV peak

Typical current (all phases) = 4.2-ampere peak

(300 Hz, rms = 1.33 amperes)

Test No. 5 - Same as Test No. 3 except with 1.5 ohms across the broken delta.

Results

There were some attempts to go into ferroresonance but without success. (See oscillograph Nos. 7A, and 7B) There were no overvoltages on the pt's. The bus voltages settled down as follows:

AØ = 82 kV rms

BØ = 71 kV rms

CØ = 77 kV rms

BEST DOCUMENT AVAILABLE

Test No. 6 - Test No. 5 was repeated with the same results.

Test No. 7 - Deenergize bus 2, section 3, with pcb 5098 with following MOD's closed: 5070, 5080, 5063, 5065, 5097, 5099, 5117, and 5119.

Results

There were persistent attempts to go into ferroresonance but without success. (See oscillograph Nos. 8A, 8B, and 8C) There were no overvoltages on the pt's. The bus voltage settled down as follows:

AØ = 76 kV rms

BØ = 70 kV rms

CØ = 71 kV rms

Test No. 8 - Repeat Test No. 7 with 1.5 ohms in broken delta.

Results

No ferroresonance and fewer attempts made to go into ferroresonance than in Test 7. (See oscillograph Nos. 9A, 9B, and 9C) There were no overvoltages. The bus voltages settled down to the following values:

AØ = 76 kV rms

BØ = 70 kV rms

CØ = 71 kV rms

The bus voltages were also recorded with magnetic tape, oscilloscope pictures, and peak reading voltmeters. There were no higher voltages recorded due to either ferroresonance or MOD operation than those recorded on the oscillograph.

Computer Studies

Computer studies of the ferroresonance problem were initiated for two reasons: First, it was hoped that the studies would provide guidance in the tests by indicating some appropriate remedial actions, and secondly, the transients computer program was being reviewed for use in planning studies and this provided an opportunity for familiarization.

The computer program in question is the Bonneville Power Administration's Electromagnetic Transients Program (EMTP) which is now one of the leading transients programs in the industry. It is widely used in the study of voltage surges on power systems, replacing the transient network analyzer in many studies. This study required the use of the program's saturable characteristic feature to represent potential transformers.

Figure 10A is a plot of a computer run showing the A-phase voltage on the load side of the circuit breaker before and after breaker operation. The transition into ferroresonance begins as the breaker opens at approximately 16 milliseconds and the greatest voltage spikes occur in the transition period below 300 ms before a regular pattern appears. Figures 10B and 10C are a continuation of the run.

Figures 11A and 11B show a plot of the A-phase current into the potential transformer. Note that it is negligible initially when the pt is operating in the linear region, increasing afterward to 7-8 amp spikes during ferroresonance.

By adding a 1.5-ohm resistor across the open-delta of the pt secondaries completely different results were obtained. Figures 12A and 12B are a computer plot of voltage during this run. They show that transient conditions settled out within 150 ms and no ferroresonance was indicated. The corresponding current is shown in figures 13A and 13B to produce a few spikes before dropping back to a negligible value.

The final computer plot, figures 14A and 14B, is run without the resistor. Instead a .005 uF capacitor was connected phase-to-ground on each 400-kV bus, and although the result was not as well defined as in the preceding run, this did give a good indication that ferroresonance was prevented here also.

It should be stated that some apprehension of the computer results has existed from the beginning. This was caused mainly by lack of experience in running ferroresonance studies. By comparison, during the past several years, we have developed a level of confidence in some other types of computer studies such as power flow, fault analysis, and transient stability studies which just is not present in ferroresonance studies due to lack of experience and a lack of positive correlation of results with test data or the literature. No discredit to the program is intended here.

Several difficulties were overcome during this study. Suitable data on the potential transformers, burdens, and bus capacitances were found to be critical in the attempts to get reasonable answers and later to duplicate test results. Integration step size was found to be important also. We settled on 20 micro-seconds as being satisfactory in the runs. In correlating with the test results, the most significant finding has been that in neither could ferroresonance be stopped with any remedy short of disconnecting the potential transformers from the source by opening the disconnect switches. Stopping ferroresonance should be distinguished from preventing ferroresonance - it was found that ferroresonance could be prevented from happening much more easily than it could be stopped once it had begun.

Another important conclusion reached was that the study results were so sensitive to the impedance data that no single cure-all could be found to cover all instances which might occur in the TVA system, that is a fix at one location may not work at a second location.

The capacitance of Bus 2 - Section 3 was measured with a Doble test set and were:

A-B 331 pF

B-C 330 pF

C-A 141 pF

A-G 1676 pF

B-G 1312 pF

C-G 1295 pF

The secondary pf burdens were measured to be:

Z:A Ph. - B Ph. = 167 ohms at 16.6°

Z:B Ph. - C PH. = 177 ohms at 16.6°

Z:C Ph. - A Ph. = 225 ohms at 16.4°

The excitation curve for the pt's was provided by the manufacturer.

Each pcb was assumed to be 500 pF per phase when the pcb was open.

Discussion and Fix

The initial fix of the ferroresonant problem was to establish a switching procedure whereby as soon as a 500-kV pcb is opened, its MOD's would be opened also. Also, if the bus is tripped by relay action, the MOD's will be opened as soon as possible, even though the indicating voltmeters are showing a high voltage.

The results of the tests and the computer studies both show the voltage during ferroresonance to not be abnormally high, 800-kV peak was measured during the tests and this agrees with the computer studies. The pt's are normally subjected to 408-kV-volts peak so an 800-kV spike represents about two per unit voltage which the pt's should be able to stand for a short time. The current in the primary of the pt's measured 4.2 amperes peak for a duration of 1.67 ms. The rms value of current should be 4.2 x .707 (1.67/ 8.33) exp. 1/2 = 1.33 amperes. This amount of current flowing in the pt primary winding, which has a resistance of 9300 ohms, produces 16.5 kW. It is easy to see why ferroresance does thermal damage to the pt.

An interesting result of the tests is that once ferroresonance is started, switching in resistance on the pt secondries will not stop it. The only case where secondary resistance was effective is where it was connected across the broken delta.

In deciding on a permanent fix, there was some apprehension about relying on the 1.5 ohm resistor in the broken delta alone. It was proposed to add .005 uF capacitance per phase to each bus in order to reduce the voltage when the bus is energized through open pcb's. 500-kV coupling capacitors will be used to provide this capacitance. These coupling capacitors will be temprarily installed on Bus 2, Section 3 at Watts Bar to see if the ferroresonant problem is eliminated. It is realized that this is an expensive fix, however, the conseuences of pt failures are so severe that it is considered justifiable. Computer studies showed the effectiveness of the 1.5-ohm resistor in the broken delta to vary with pt burden and the pt's to still have some ferroresonance with the additional capacitance on the bus. However, based on the correlation obtained with actual test measurements, it is suspected that the results of the computer studies are somewhat pessimistic.

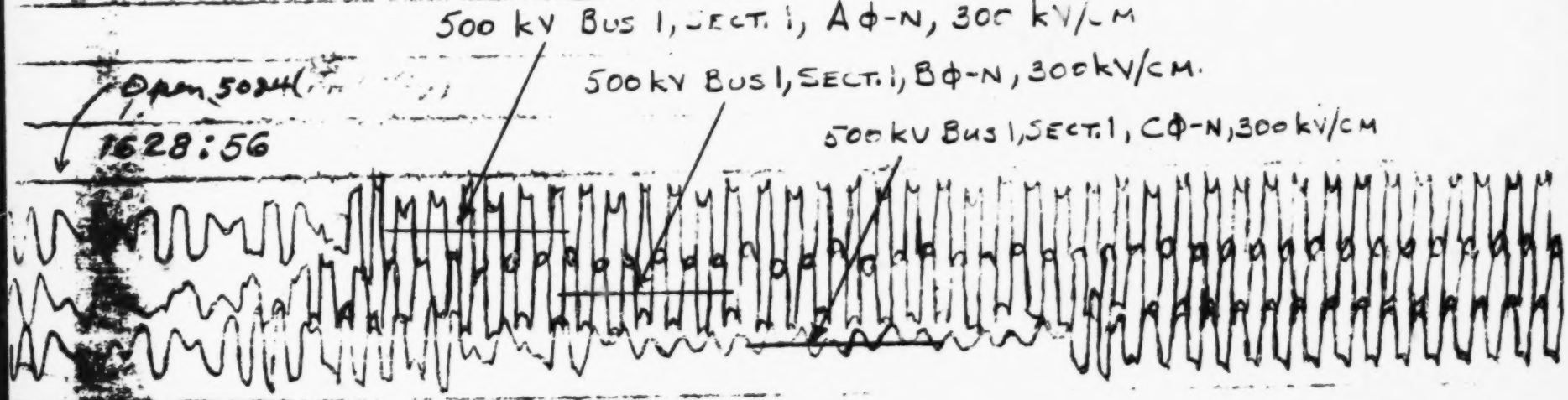
Other fixes which were considered were automatic opening of the MOD's after bus faults or during ferroresonance and replacing the pt's with cvt's. Additional studies must be made before these options will be used.

NO. 1

BEST DOCUMENT AVAILABLE

1628

1628



OSCILLOGRAPH NO. 1

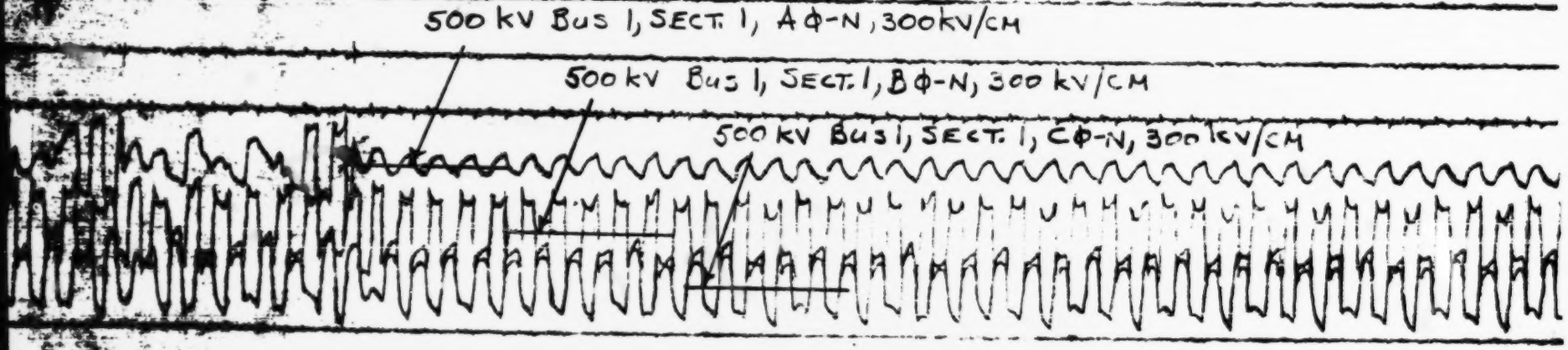
SHOWING PT'S IN FERRORESONANCE WHEN BUS 1, SECT. 1 WAS DE ENERGIZED THROUGH pcb's 5024 AND 5034.

BEST DOCUMENT AVAILABLE

NO. 1

16 49 : 06

12-8-79 at 1647 After opening 5034 ct 16

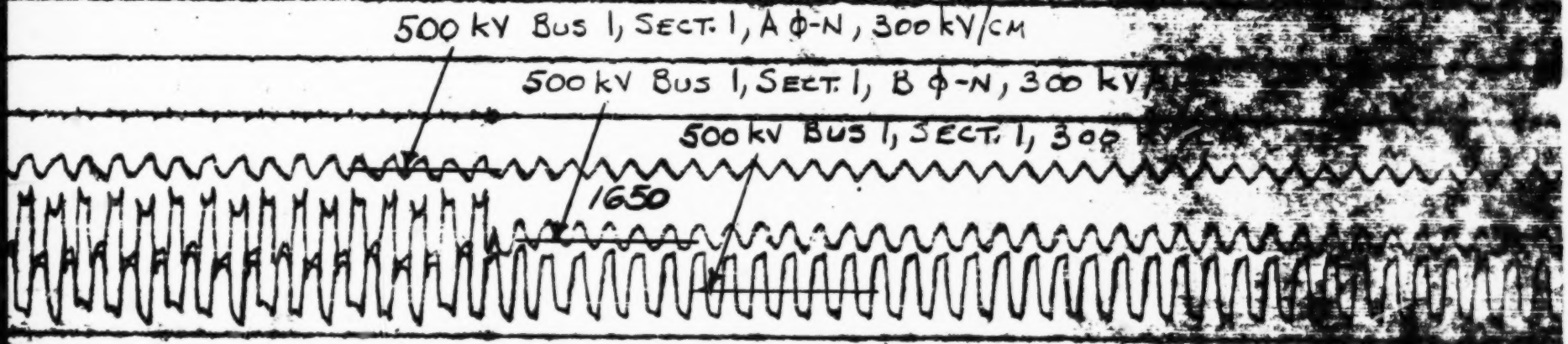


OSCILLOGRAPH No. 2

SHOWING WHERE THE A Φ PT CAME OUT OF FERRORESONANCE

BEST DOCUMENT AVAILABLE

ng 5023 & 5025 & 1650

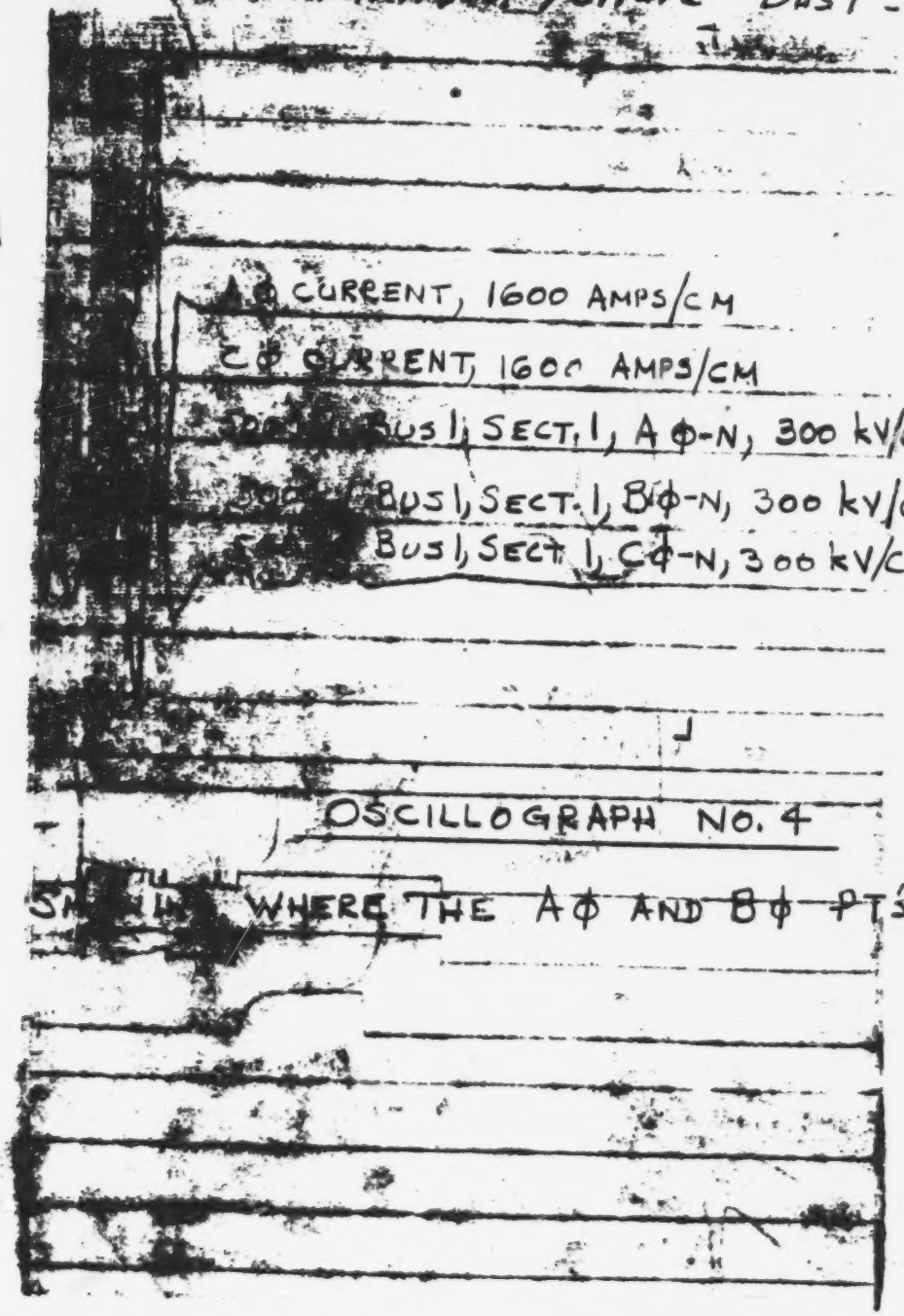


OSCILLOGRAPH No. 3

SHOWING WHERE THE B ϕ PT CAME OUT OF FERRORESONANCE

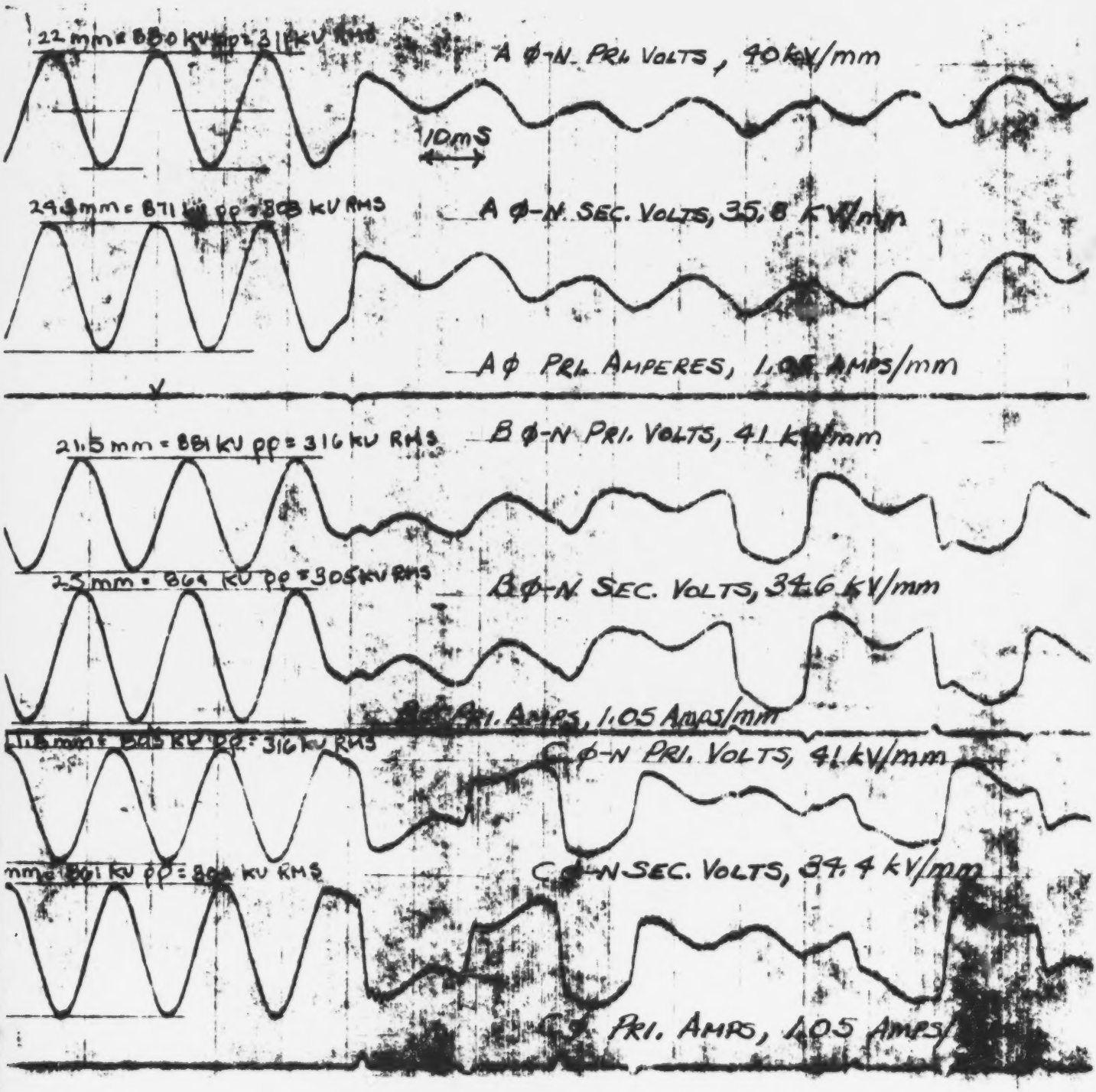
T NO. 1 Potential Circuit Failure - Bus 1

1651


CURRENT, 1600 AMPS/CM
CURRENT, 1600 AMPS/CM
Bus 1, SECT. 1, AΦ-N, 300 kV/CM
Bus 1, SECT. 1, BΦ-N, 300 kV/CM
Bus 1, SECT. 1, CΦ-N, 300 kV/CM
OSCILLOGRAPH NO. 4
WHERE THE AΦ AND BΦ PT's FAILED

BEST DOCUMENT AVAILABLE

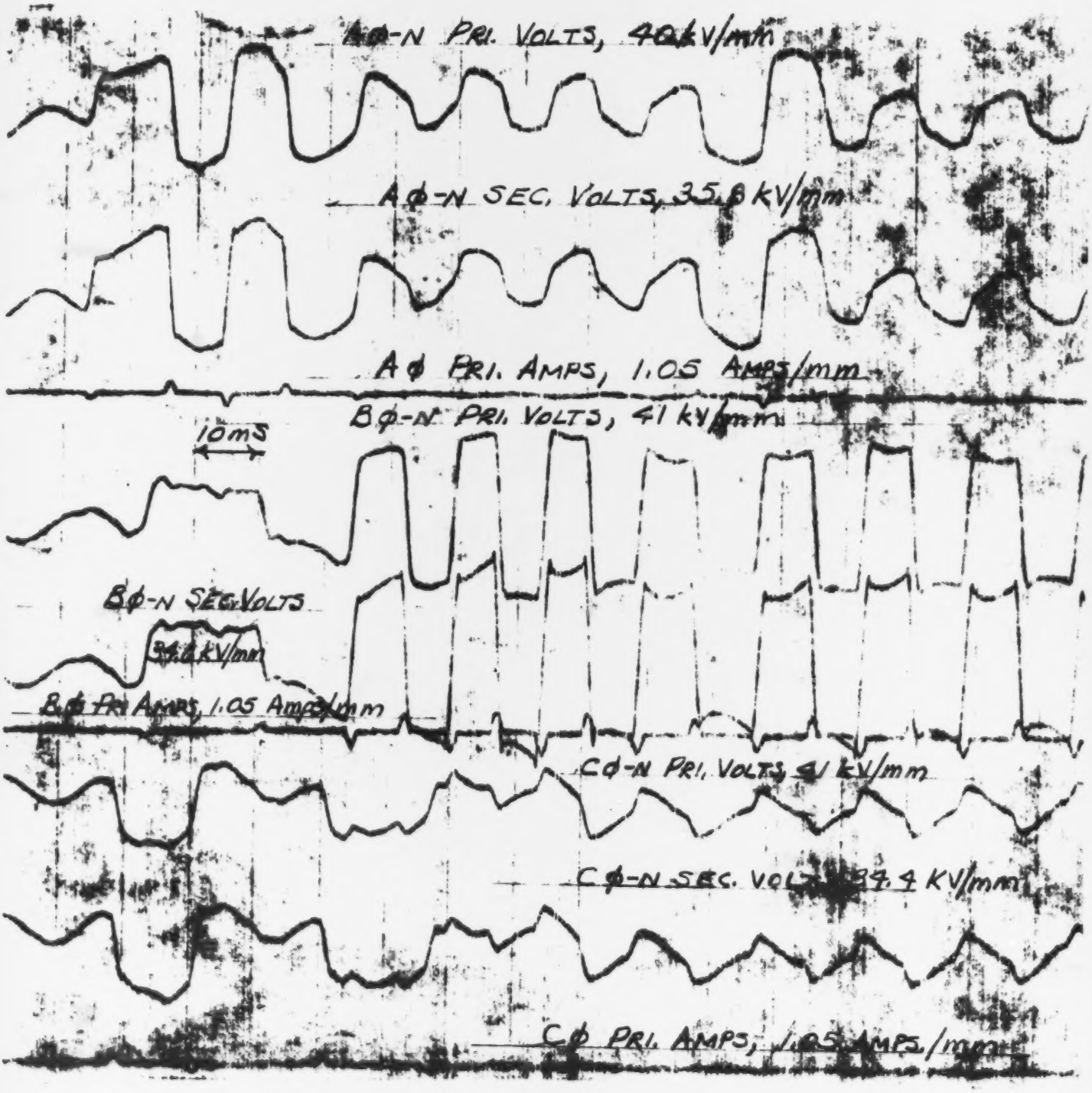
BEST_DOCUMENT AVAILABLE


22 mm = 880 KV pp = 311 KV RMS
A Ø-N PRI VOLTS, 40 kV/mm
10mS
29.3 mm = 871 KV pp = 308 KV RMS
A Ø-N SEC. VOLTS, 35.8 KV/mm
A Ø PRI AMPERES, 1.05 AMPS/mm
21.5 mm = 881 KV pp = 316 KV RMS
B Ø-N PRI. VOLTS, 41 kV/mm
2.3 mm = 864 KV pp = 305 KV RMS
B Ø-N SEC. VOLTS, 34.6 kV/mm
PRI. AMPS, 1.05 AMPS/mm
C Ø-N PRI. VOLTS, 41 kV/mm
C Ø-N SEC. VOLTS, 34.4 kV/mm
PRI. AMPS, 1.05 AMPS/

OSCILLOGRAPH 5A

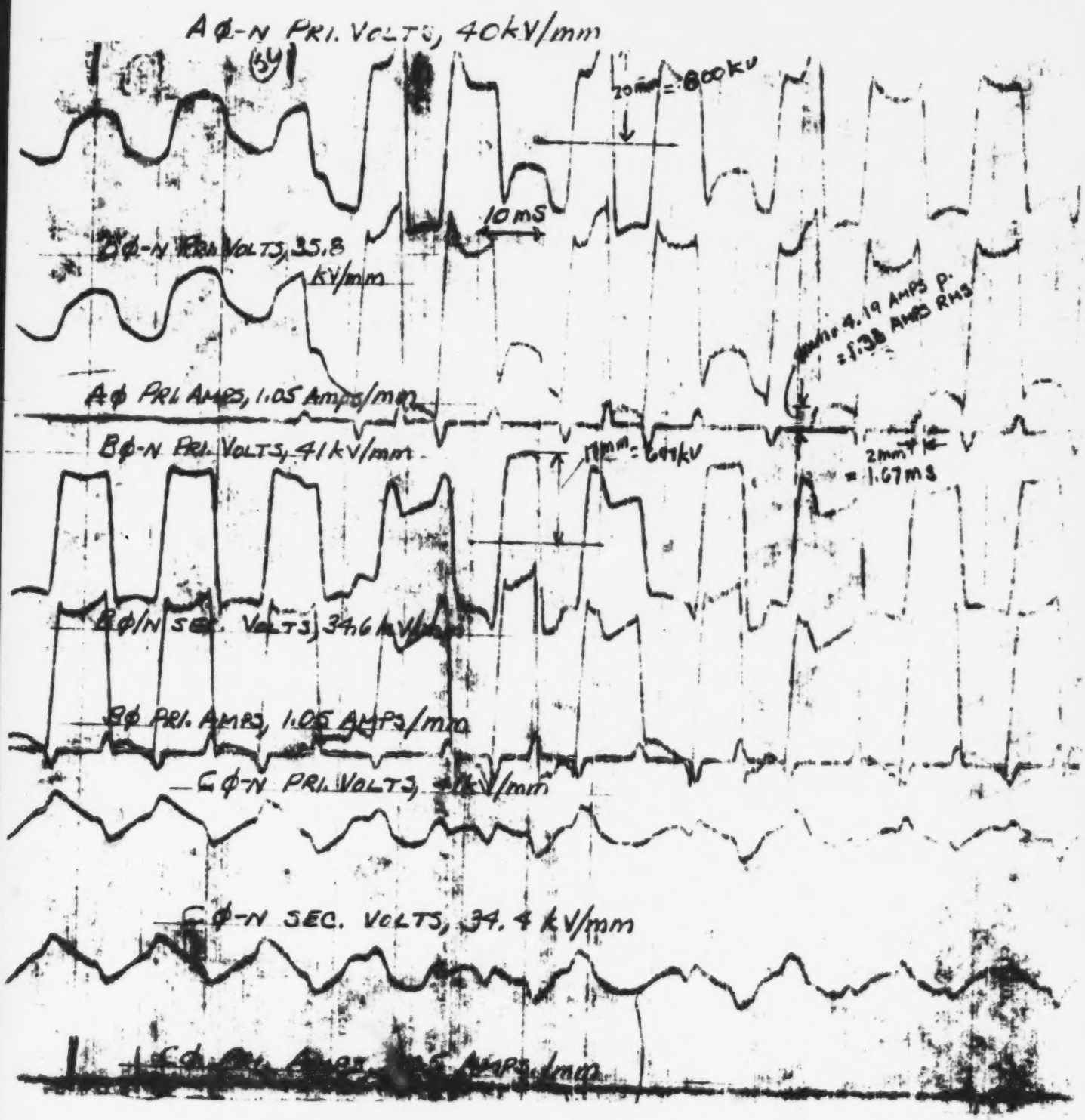
(TEST NO. 3)

BEST DOCUMENT AVAILABLE


Aφ-N PRI. VOLTS, 40 kV/mm
Aφ-N SEC. VOLTS, 35.8 kV/mm
Aφ PRI. AMPS, 1.05 AMPS/mm
Bφ-N PRI. VOLTS, 41 kV/mm
10mS
Bφ-N SEC. VOLTS
Bφ PRI AMPS, 1.05 Amps/mm
Cφ-N PRI. VOLTS, 41 kV/mm
Cφ-N SEC. VOLTS, 37.4 kV/mm
Cφ PRI. AMPS, 1.05 AMPS/mm

OSCILLOGRAPH 5B
(TEST NO. 3)

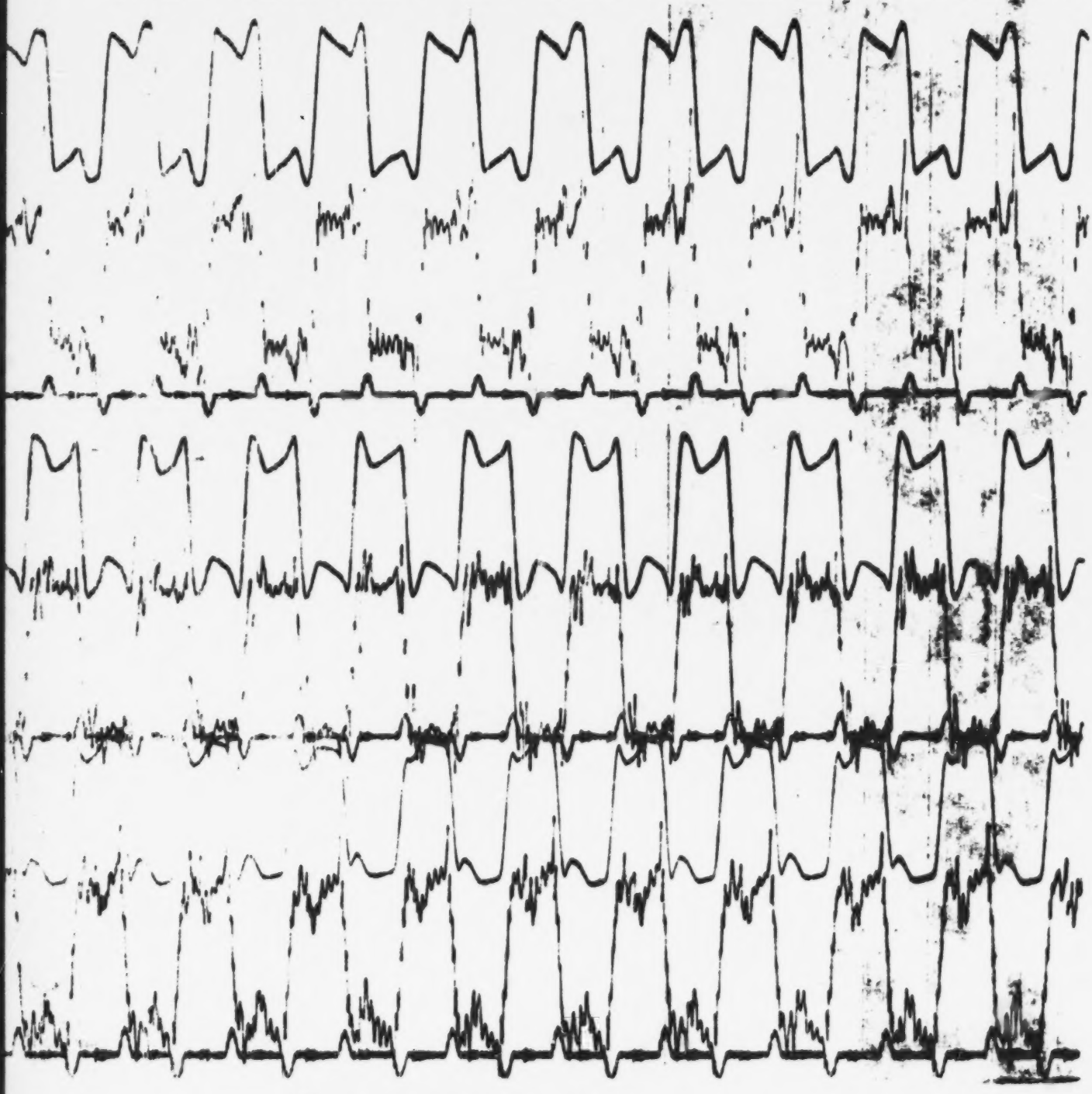
BEST DOCUMENT AVAILABLE



OSCILLOGRAPH 5C
(TEST NO. 3)

BEST DOCUMENT AVAILABLE

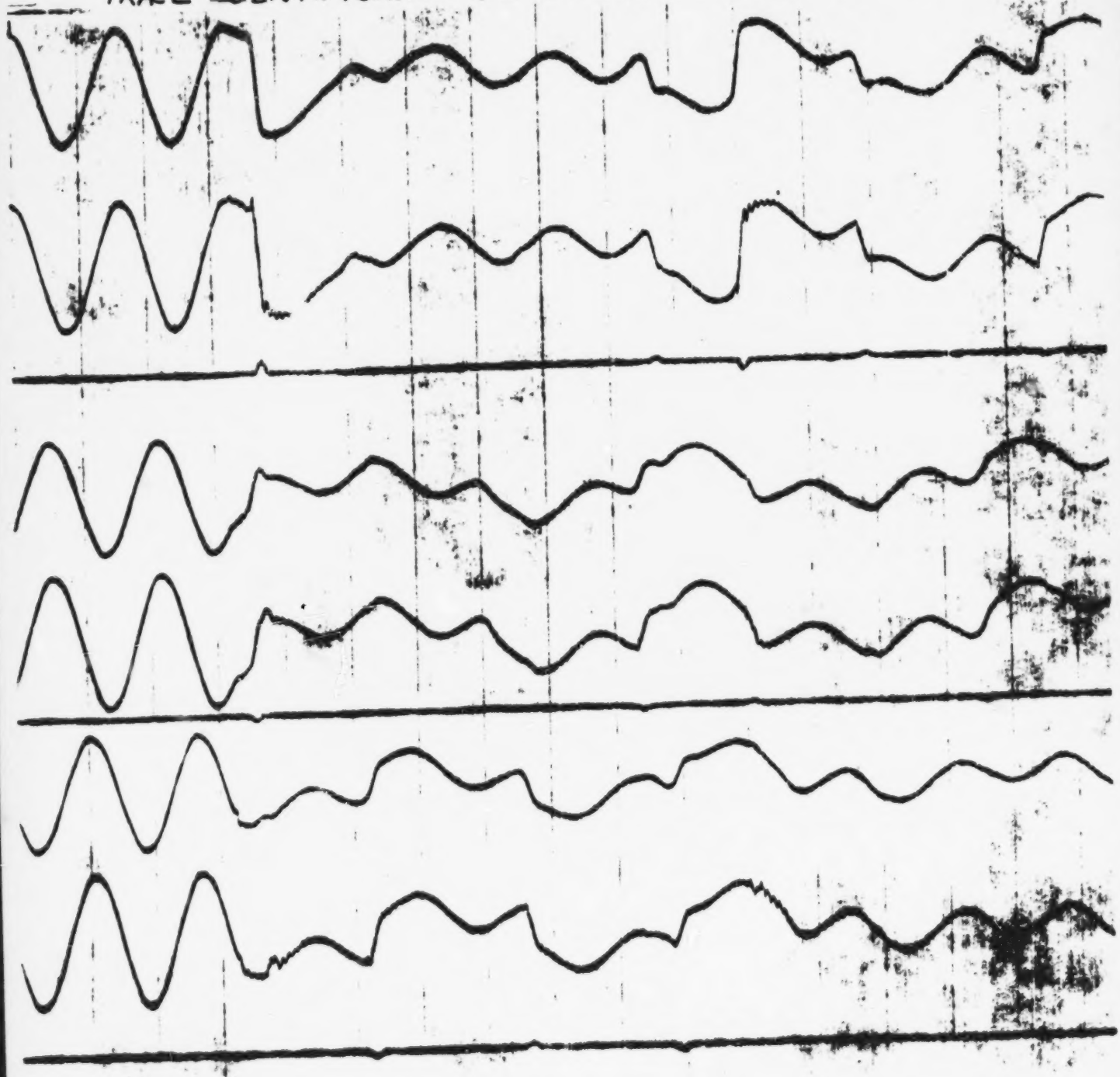
TRACE IDENTIFICATION AND CALIBRATION SAME AS OSCILLOGRAPH 5



OSCILLOGRAPH No. 6
(TEST No. 4)

BEST DOCUMENT AVAILABLE

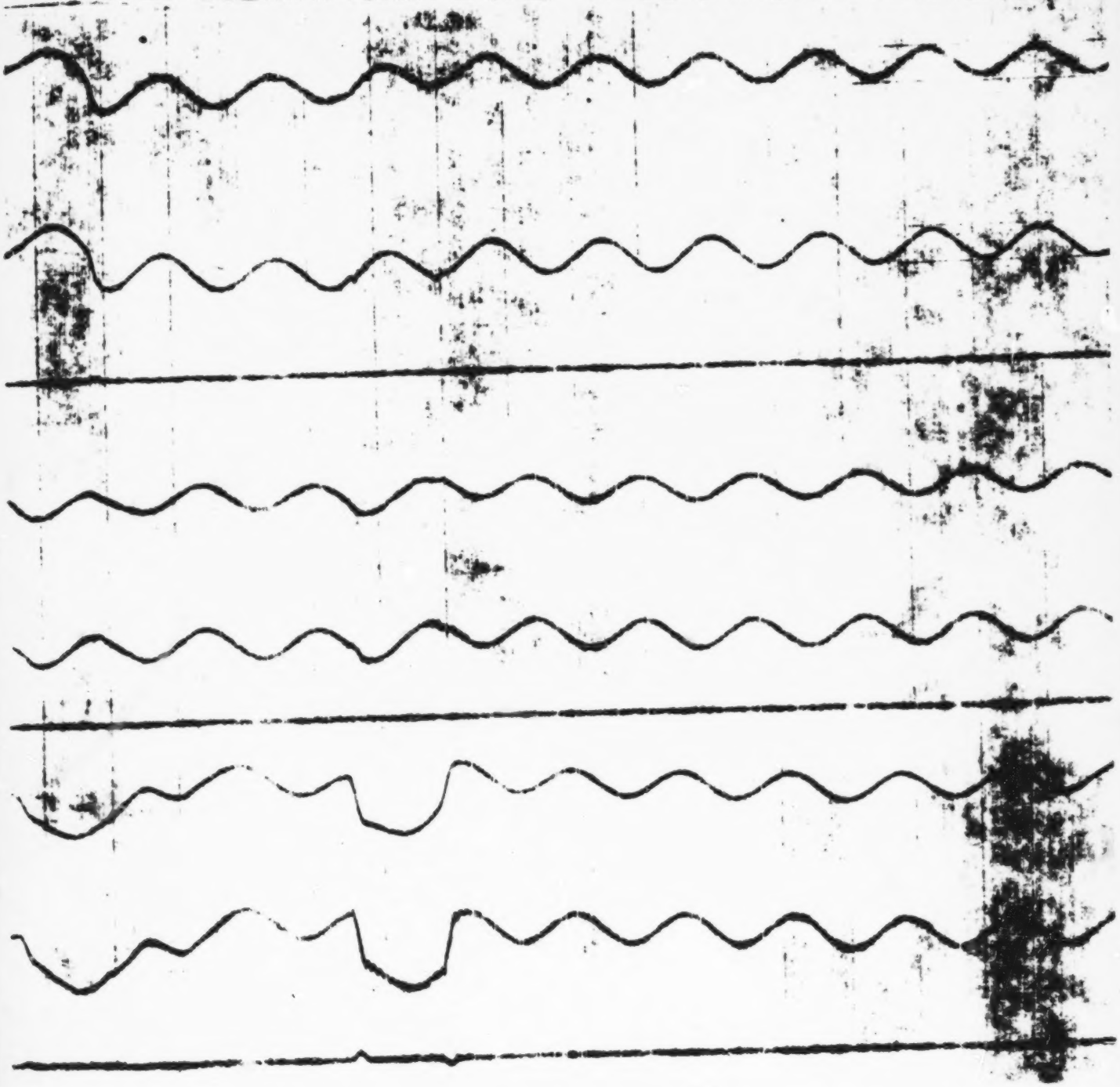
TRACE IDENTIFICATION AND CALIBRATION SAME AS OSCILLOGRAPH 5



OSCILLOGRAPH 7A
(TEST NO. 5)

BEST DOCUMENT AVAILABLE

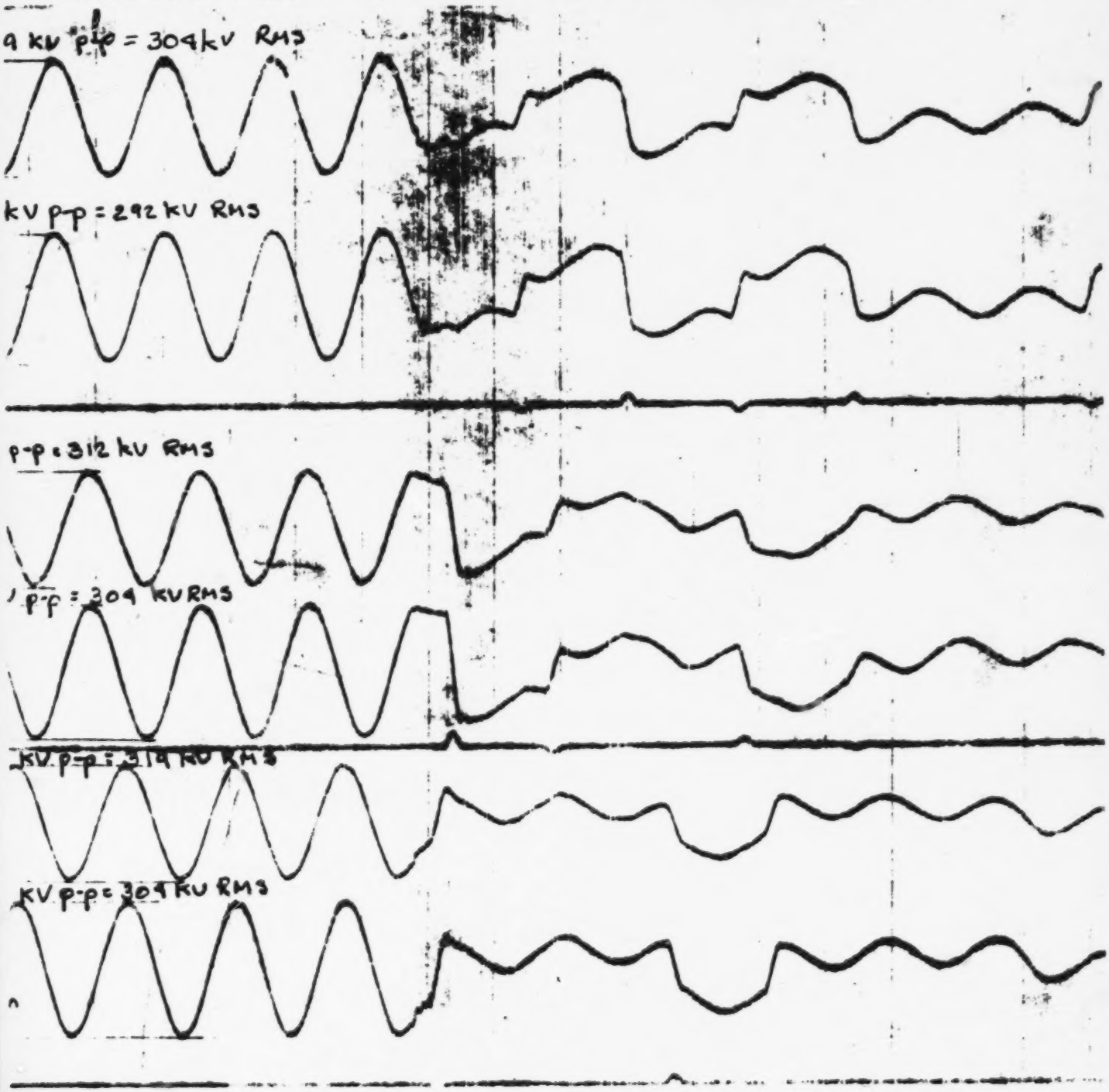
TRACE IDENTIFICATION AND CALIBRATION SAME AS OSCILLOGRAPH 5



OSCILLOGRAPH 7B
(TEST NO. 5)

BEST DOCUMENT AVAILABLE

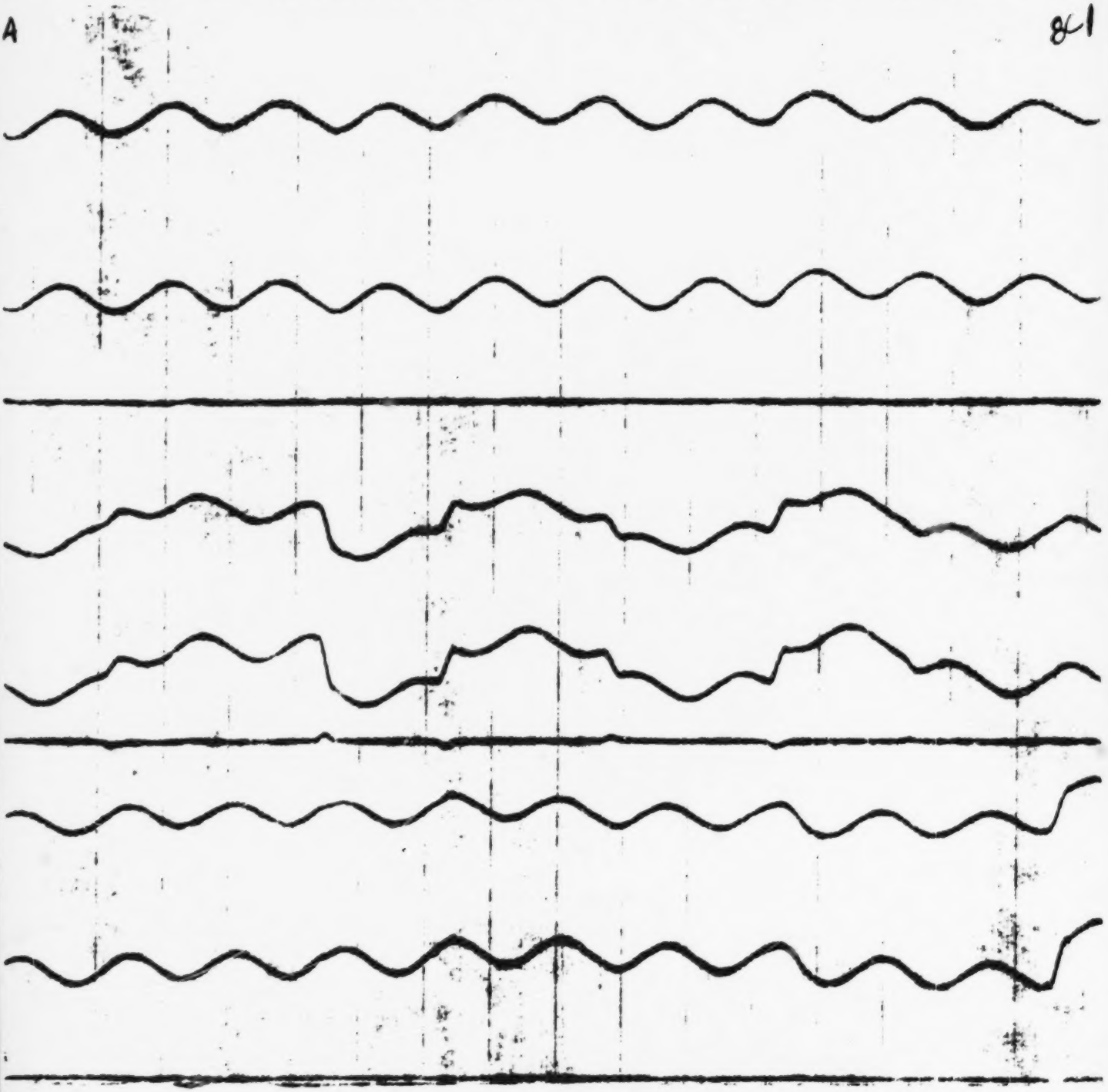
TRACE IDENTIFICATION AND CALIBRATION SAME AS OSCILLOGRAPH 5



OSCILLOGRAPH 8A
(TEST No. 7)

BEST DOCUMENT AVAILABLE

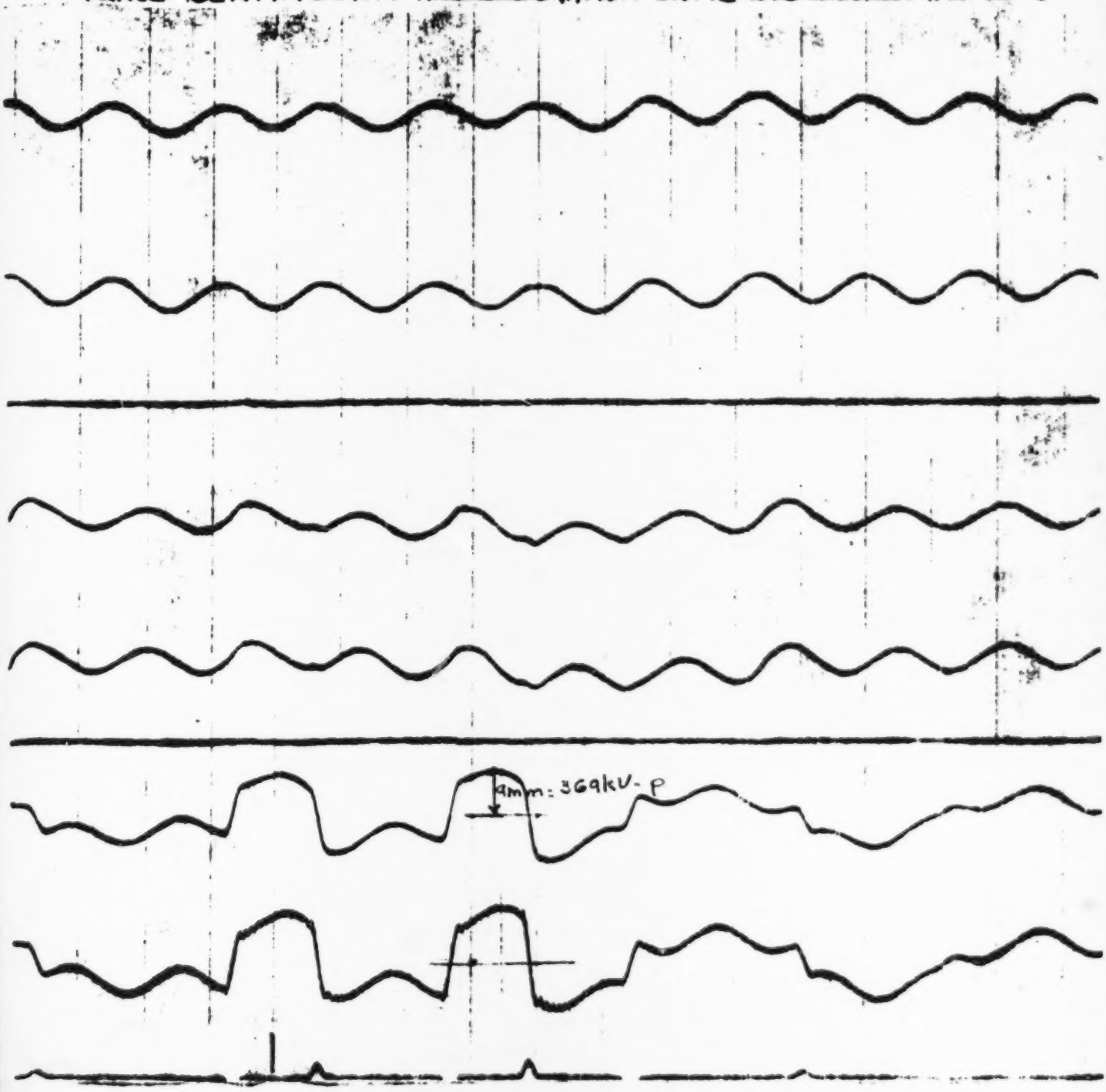
TRACE IDENTIFICATION AND CALIBRATION SAME AS OSCILLOGRAPH 5



OSCILLOGRAPH 8B
(TEST No. 7)

BEST DOCUMENT AVAILABLE

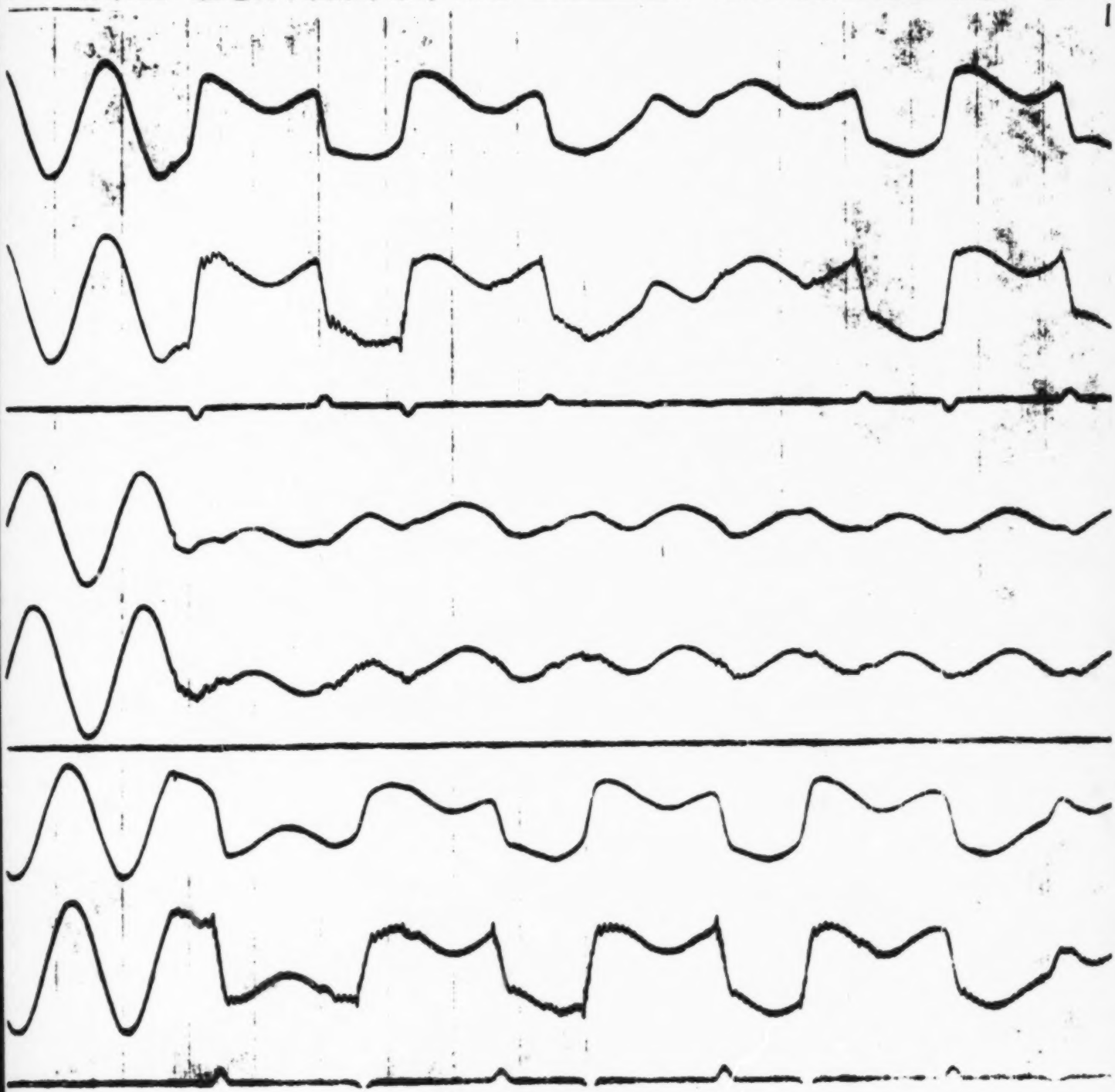
TRACE IDENTIFICATION AND CALIBRATION SAME AS OSCILLOGRAPH 5



OSCILLOGRAPH 6C
(TEST NO. 7)

BEST DOCUMENT AVAILABLE

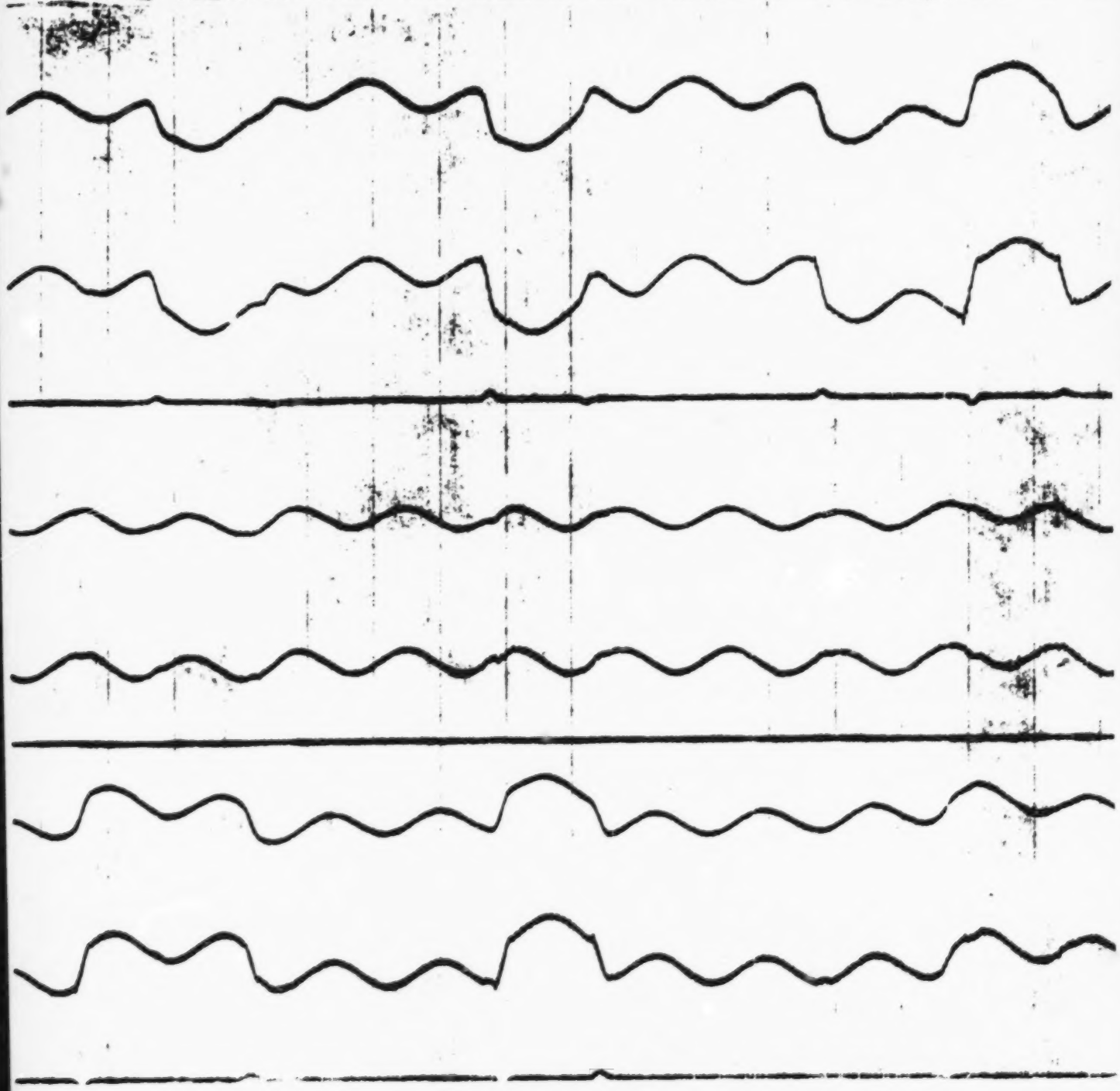
TRACE IDENTIFICATION AND CALIBRATION SAME AS OSCILLOGRAPH 5



OSCILLOGRAPH 9A
(TEST NO. 8)

BEST DOCUMENT AVAILABLE

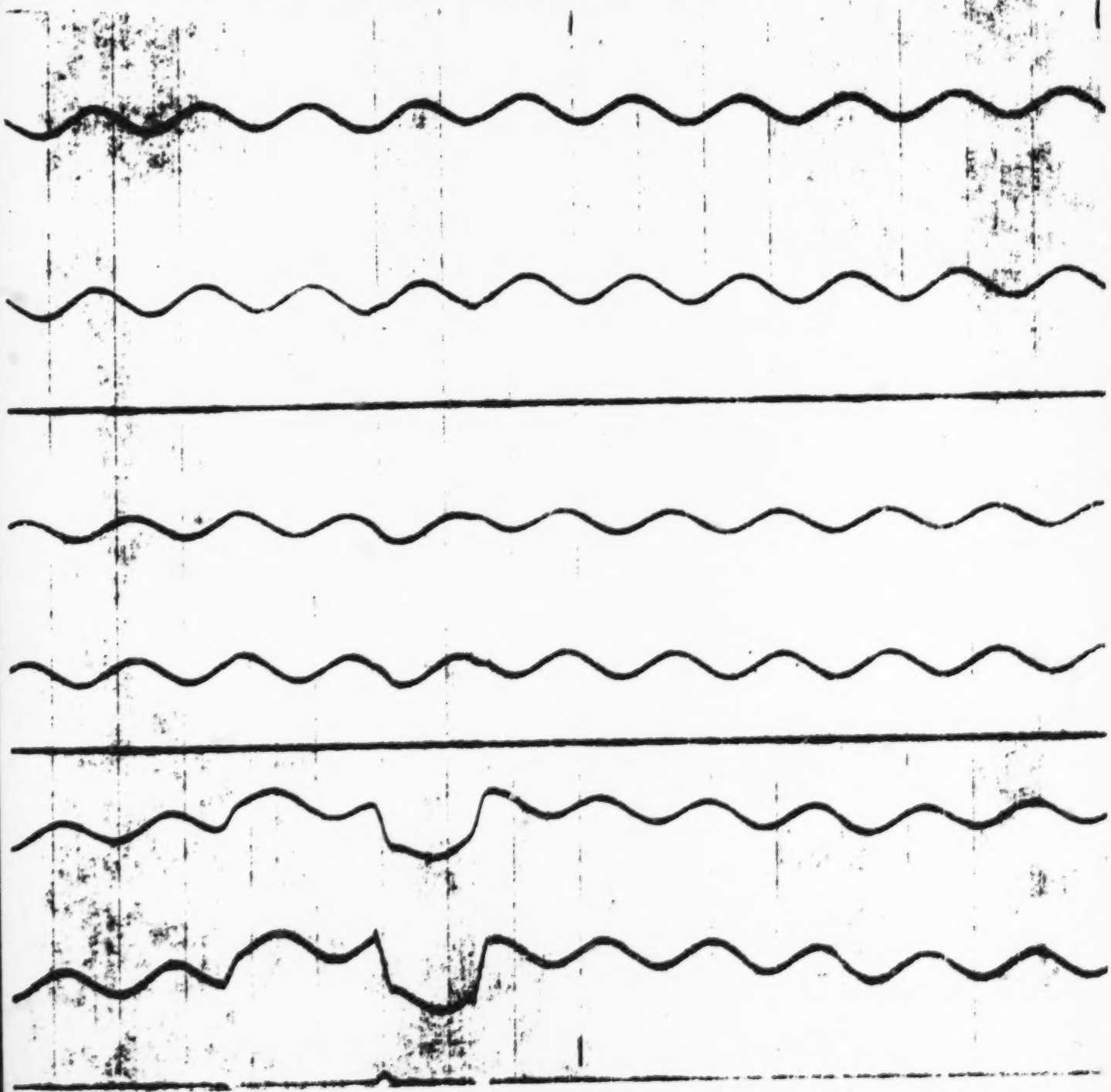
TRACE IDENTIFICATION AND CALIBRATION SAME AS OSCILLOGRAPH 5 —



OSCILLOGRAPH 9B
(TEST NO. 8)

BEST DOCUMENT AVAILABLE

TRACE IDENTIFICATION AND CALIBRATION SAME AS OSCILLOGRAPH 5



OSCILLOGRAPH 9C
(TEST No. 8)

BEST DOCUMENT AVAILABLE

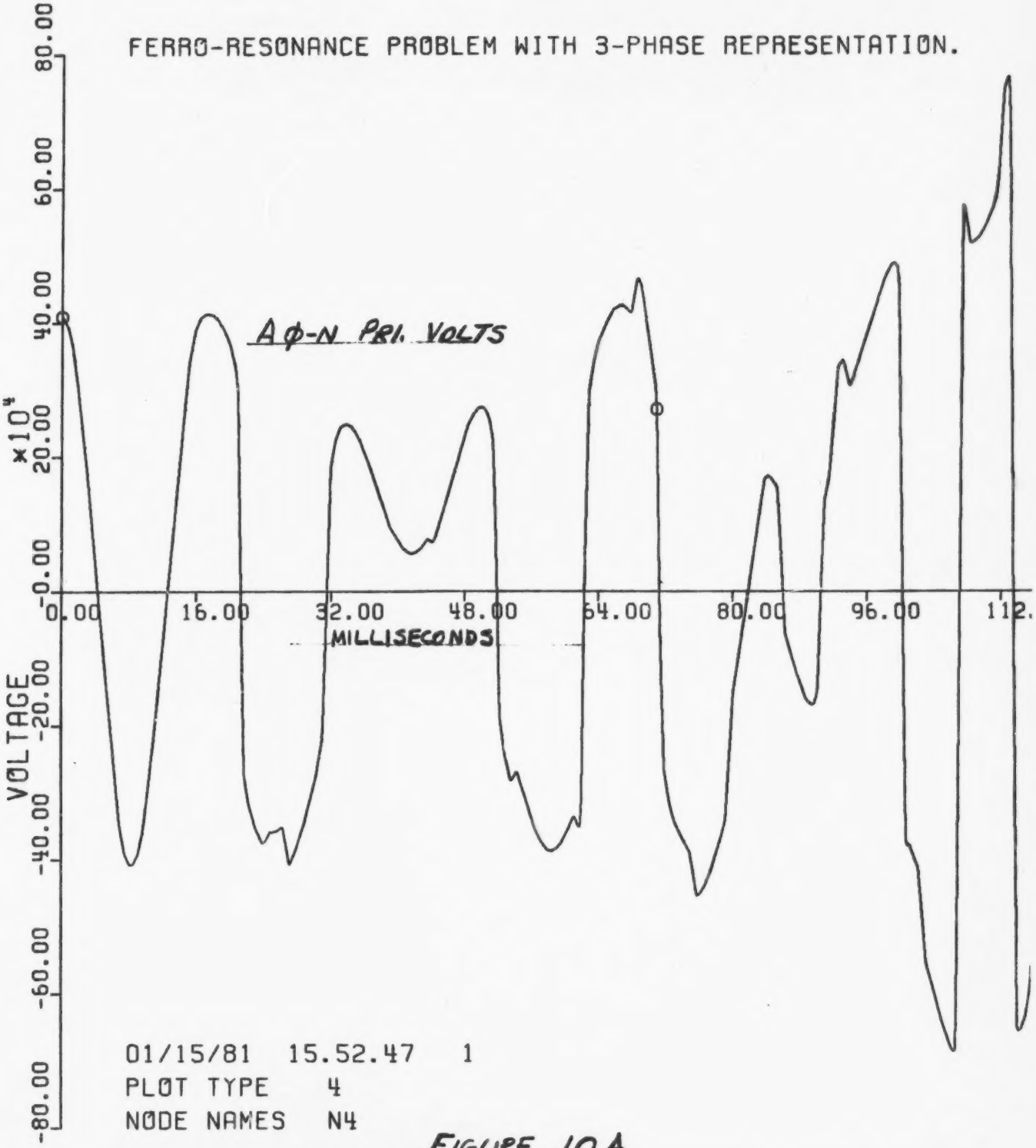


FIGURE 10A

COMPUTER STUDY SIMULATING DE-ENERGIZING BUS 2, SECT. 3 THROUGH TWO OPEN PCBS (TEST NO. 3)

BEST DOCUMENT AVAILABLE

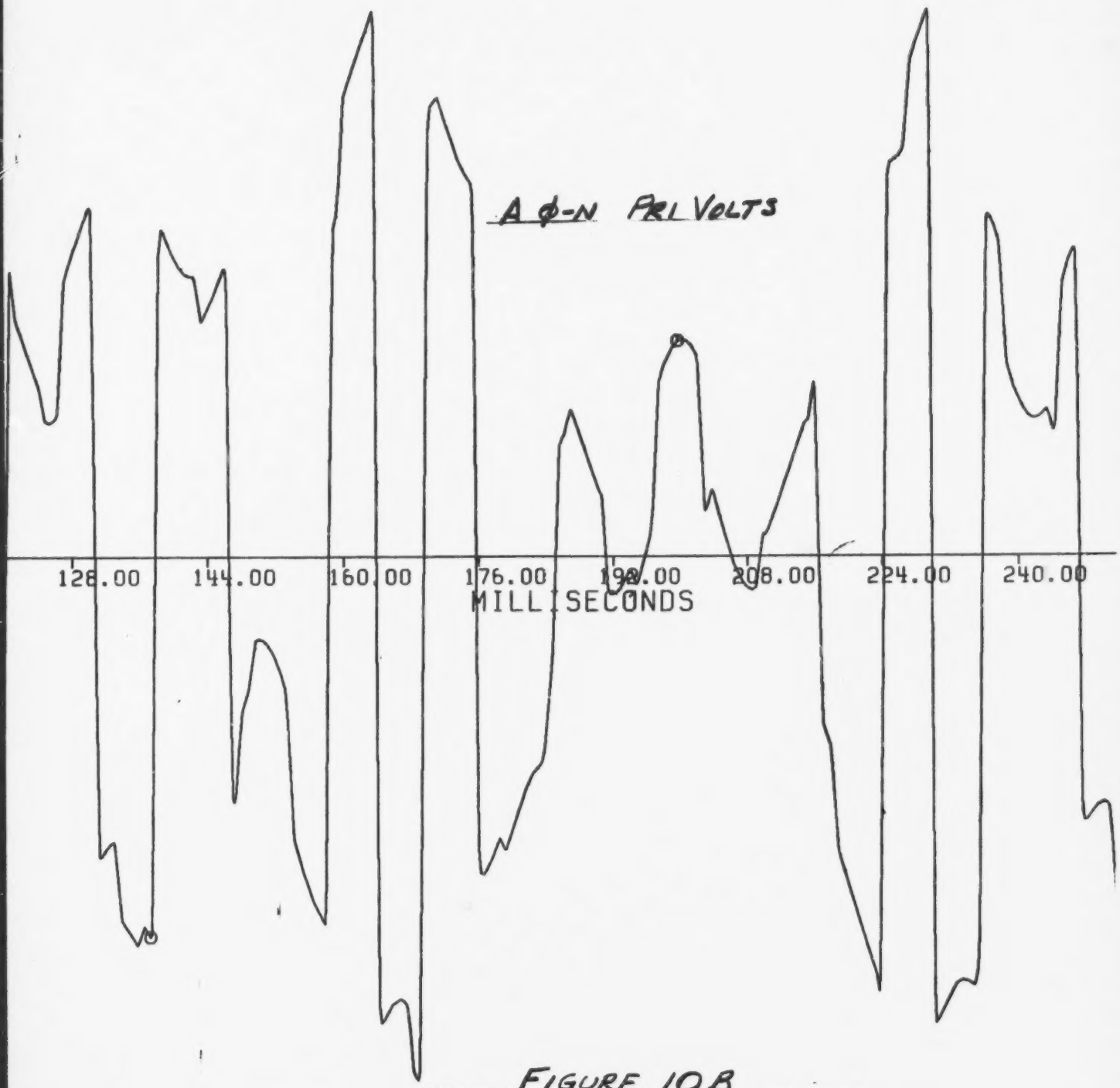


FIGURE 10B
(FIGURE 10A CONTINUED)

BEST DOCUMENT AVAILABLE

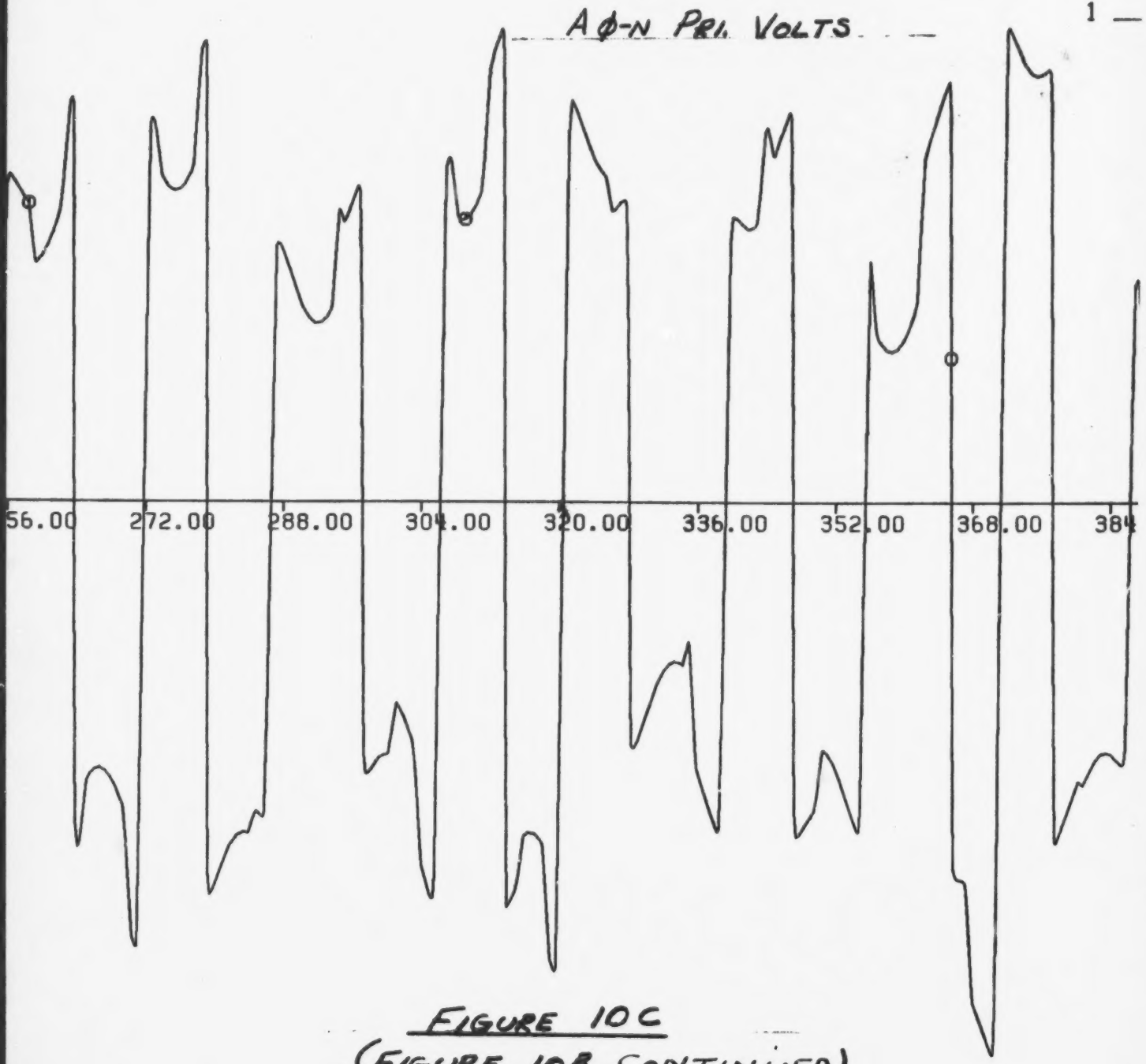


FIGURE 10C
(FIGURE 10B CONTINUED)

BEST DOCUMENT AVAILABLE

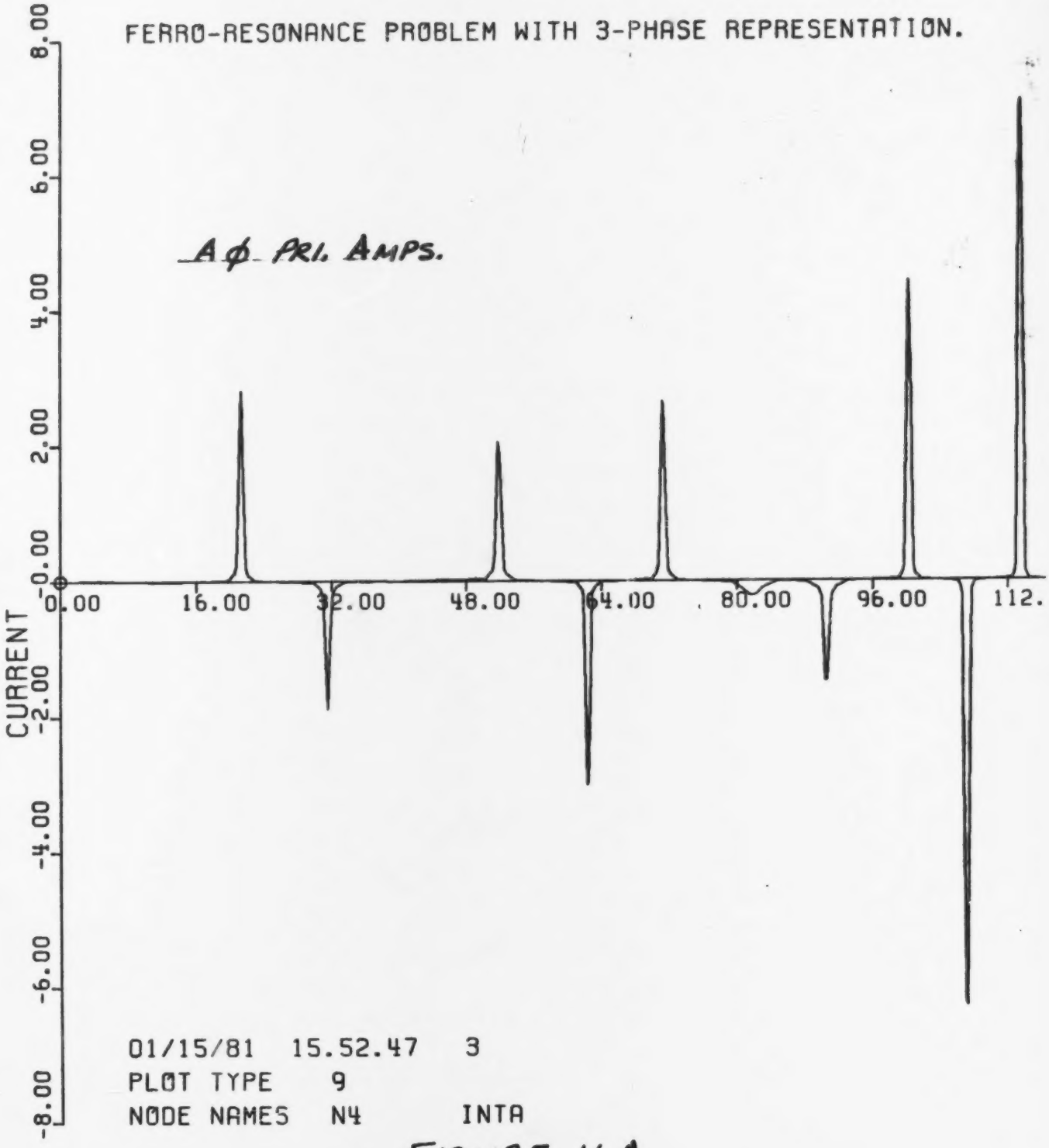


FIGURE II A

COMPUTER STUDY SIMULATING DE-ENERGIZING BUS 2, SECT. 3 THROUGH TWO OPEN PCB's (TEST No. 3)

BEST DOCUMENT AVAILABLE

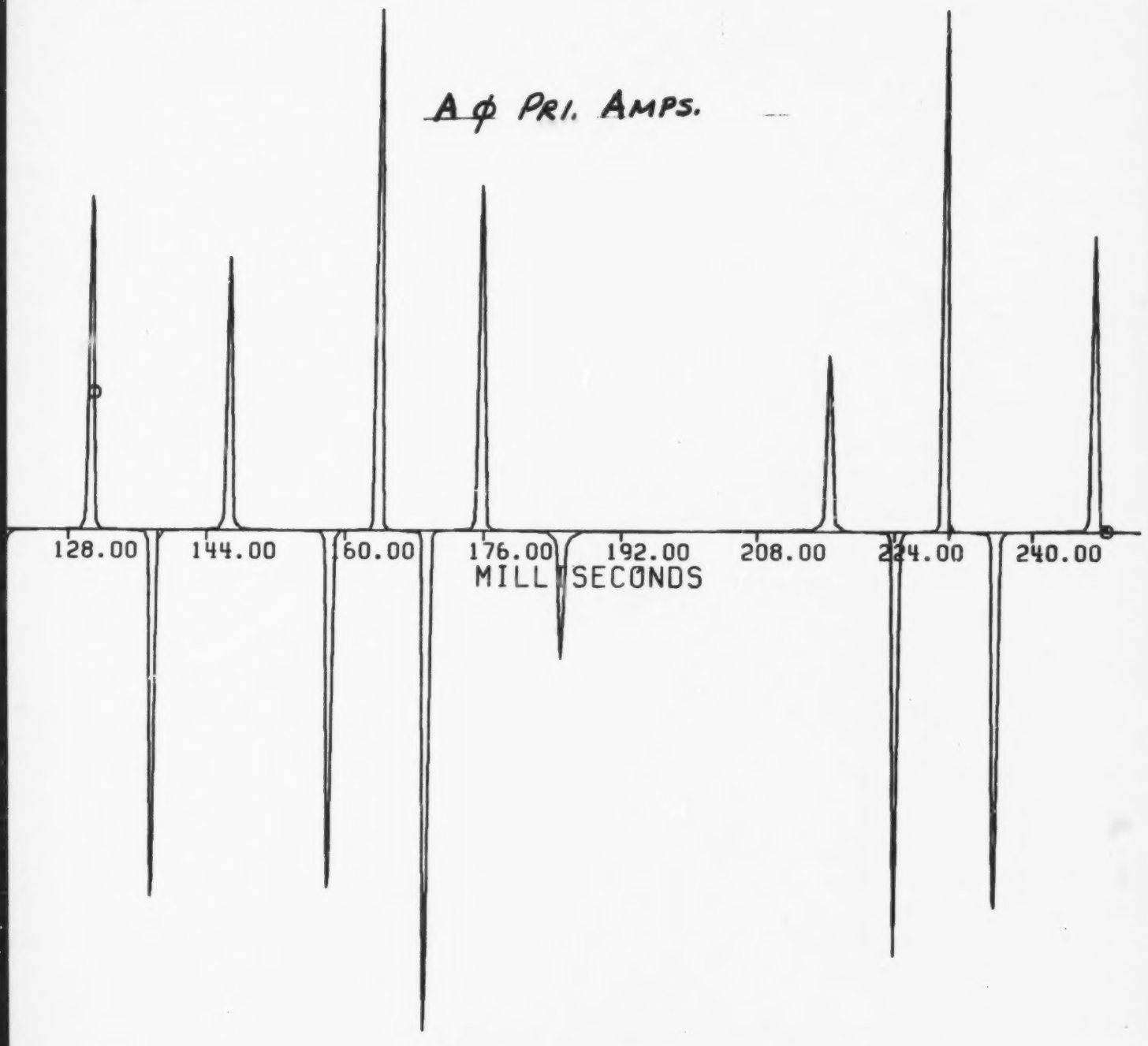


FIGURE 11B
(FIGURE 11 A CONTINUED)

BEST DOCUMENT AVAILABLE

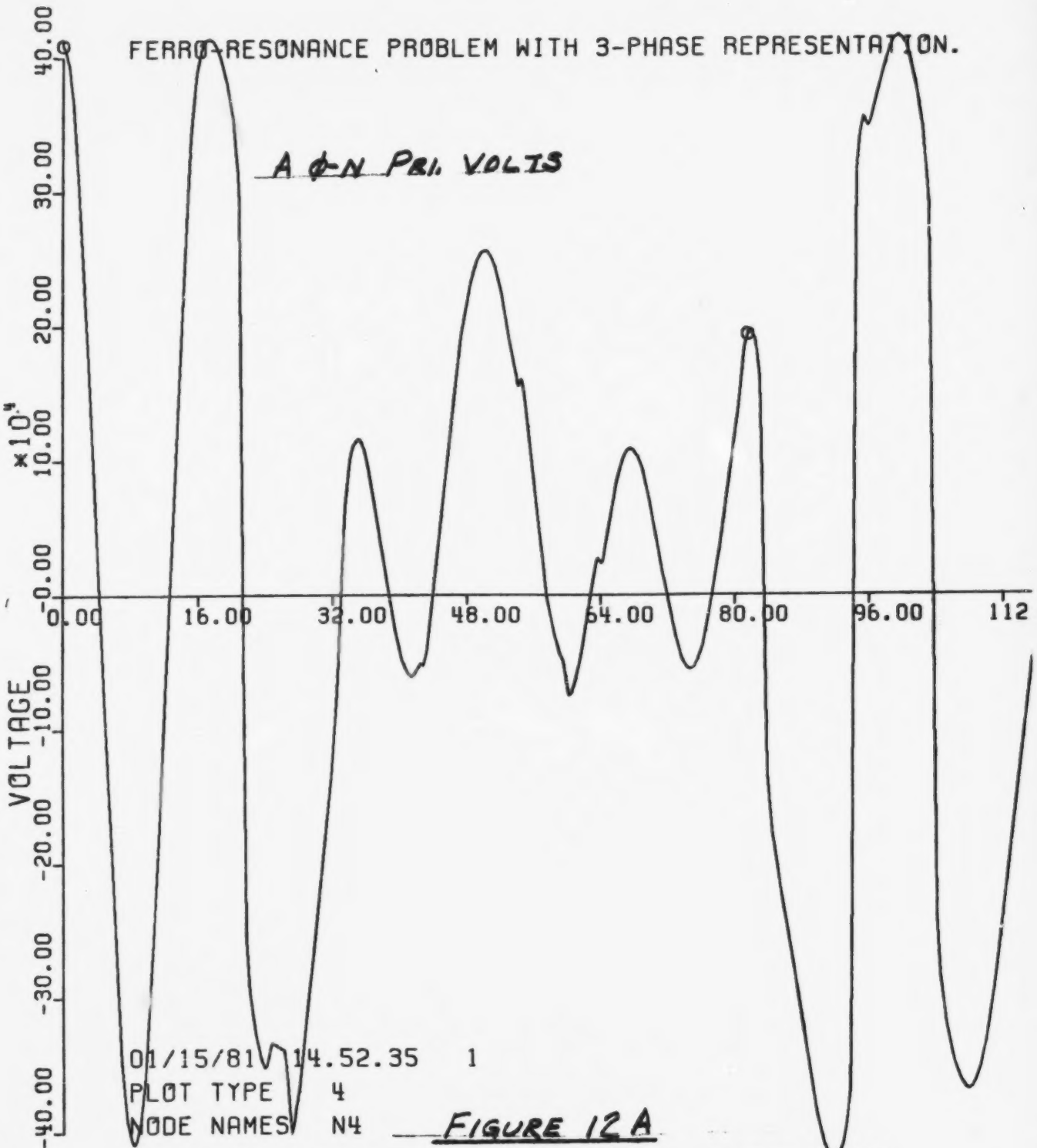


FIGURE 12A

COMPUTER STUDY SIMULATING DE-ENERGIZING BUS 2, SECT. 3 THROUGH TWO OPEN PCB'S WITH A 1.5 OHM RESISTOR IN BROKEN DELTA (TEST 5)

BEST DOCUMENT AVAILABLE

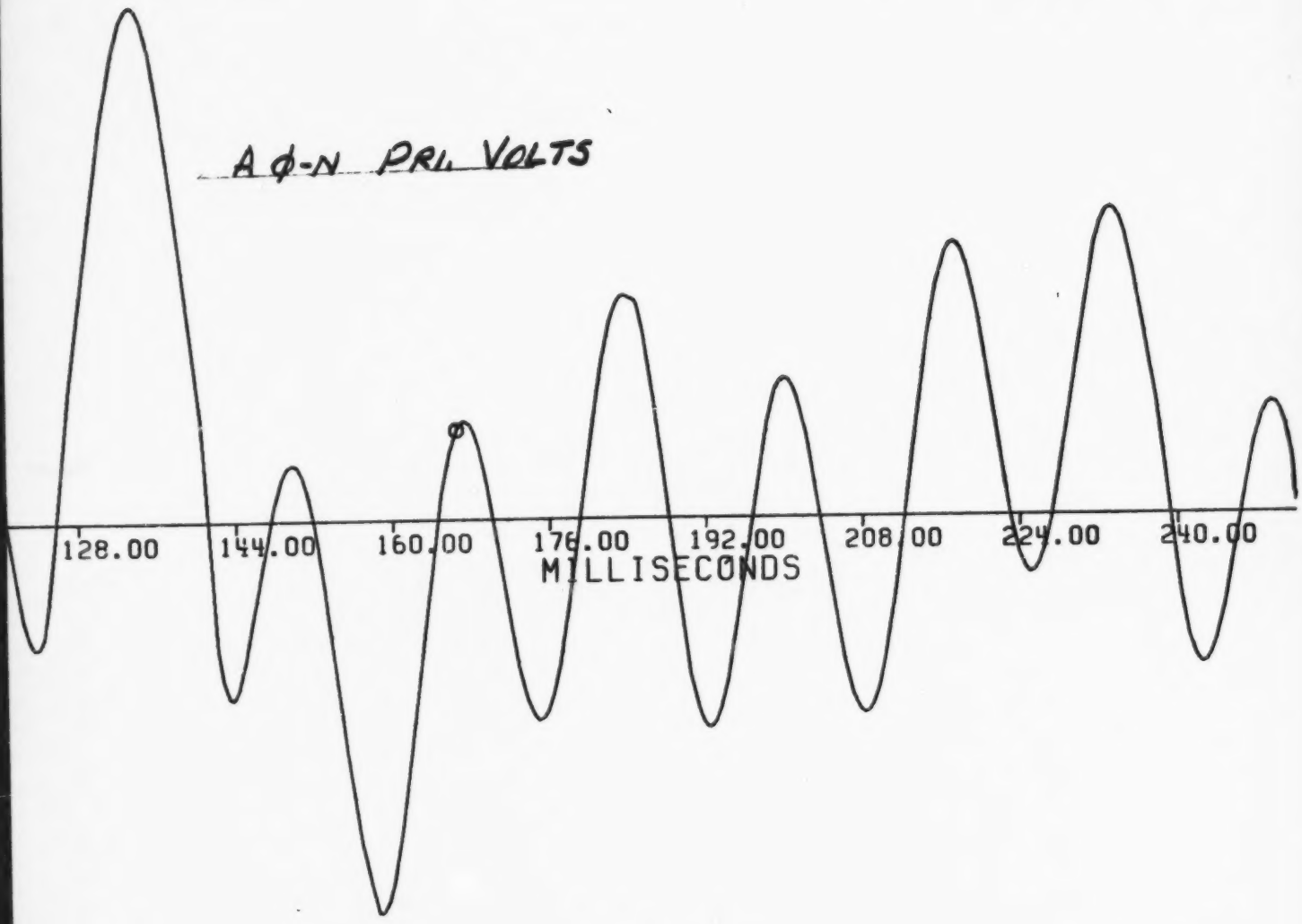


FIGURE 12B
(FIGURE 12 A CONTINUED)

BEST DOCUMENT AVAILABLE

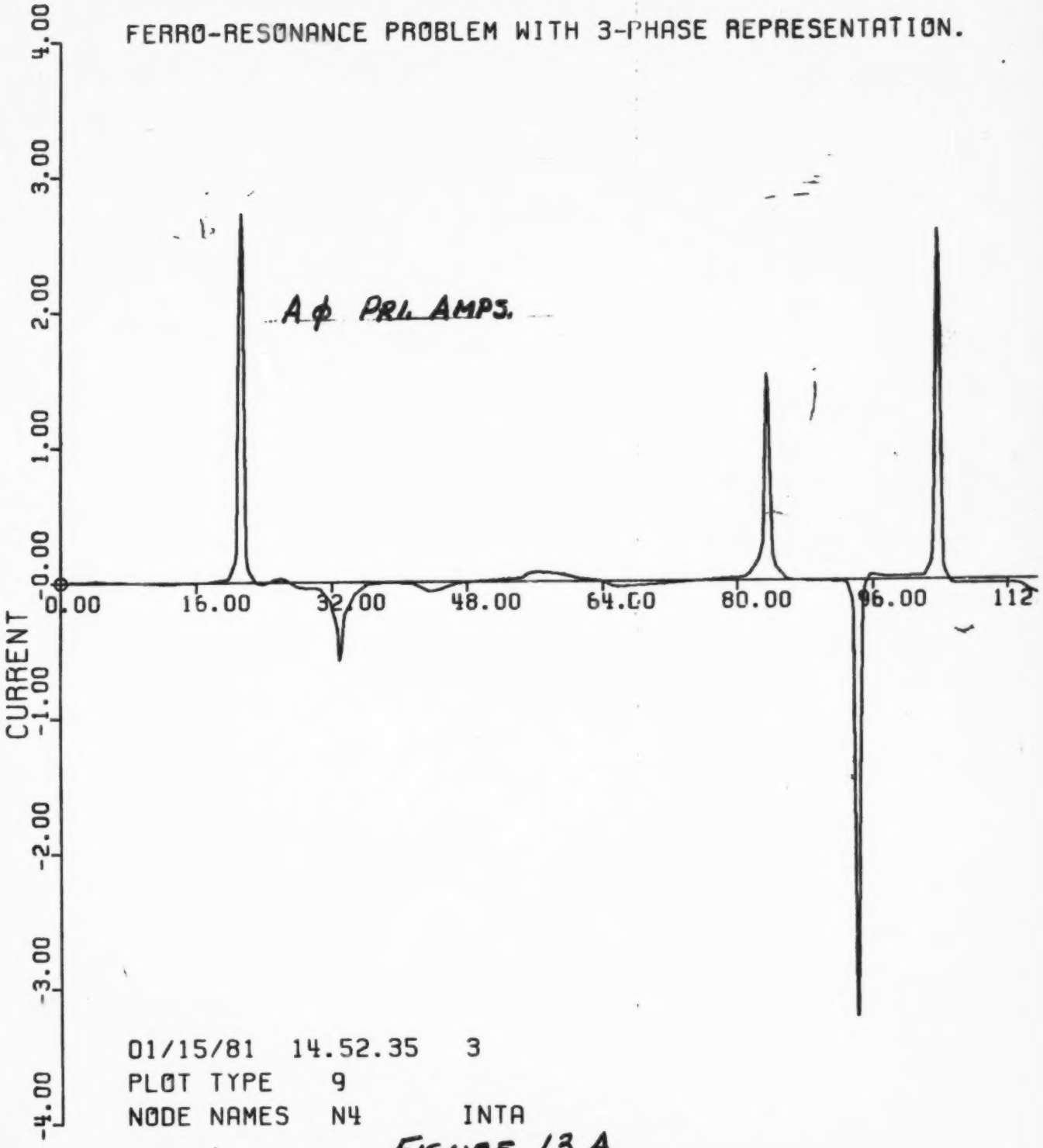


FIGURE 13 A

COMPUTER STUDY SIMULATING DE-ENERGIZING BUS 2, SECT 3 THROUGH TWO OPEN PCB'S WITH 15 OHM RESISTOR IN BROKEN DELTA. (TEST NO. 5)

BEST DOCUMENT AVAILABLE

A ϕ PRI. AMPS.

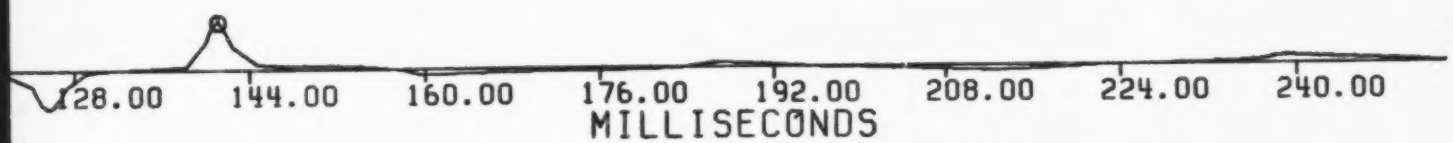


FIGURE 13 B
(FIGURE 13 A CONTINUED)

BEST DOCUMENT AVAILABLE

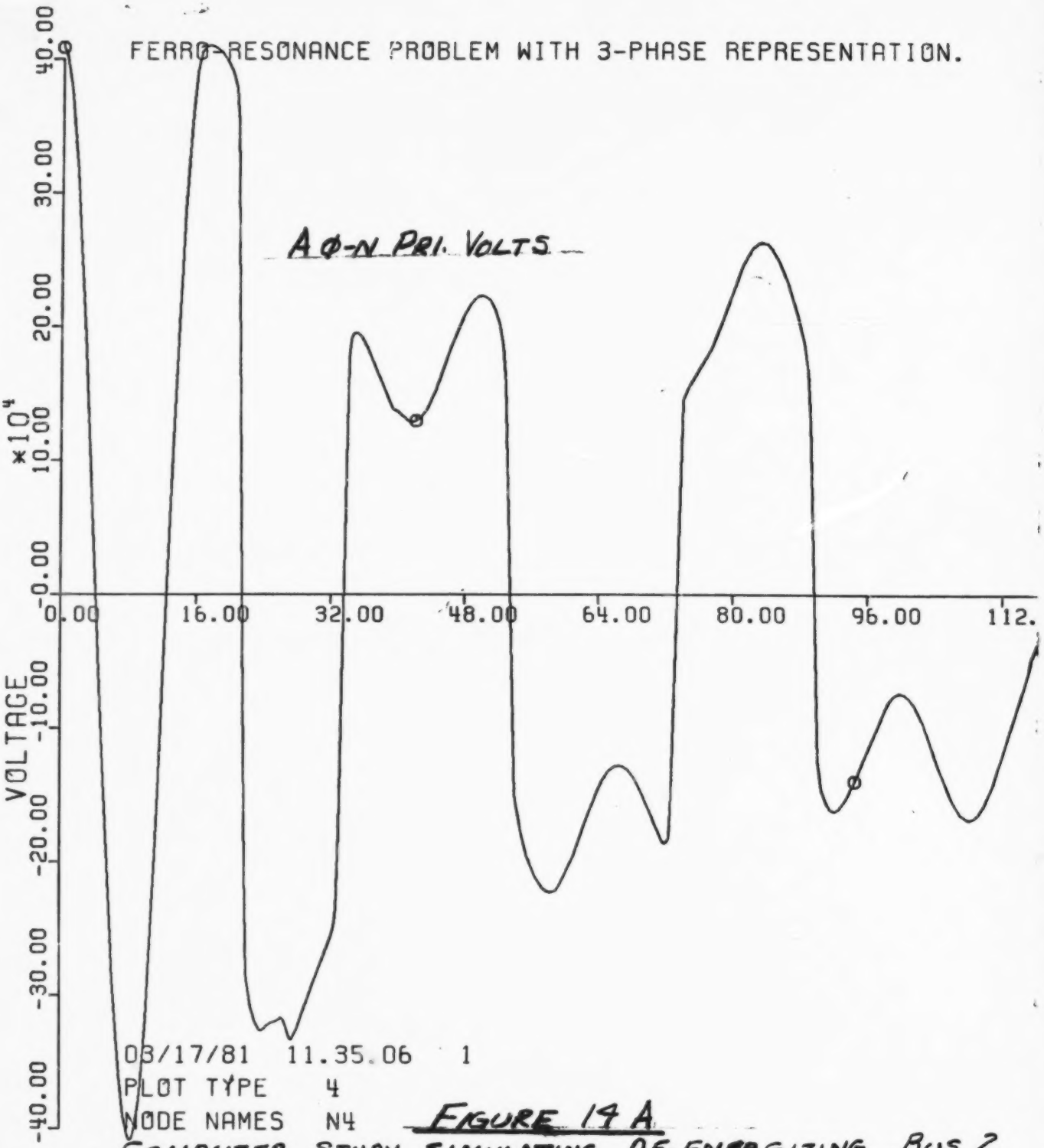


FIGURE 14 A

COMPUTER STUDY SIMULATING DE-ENERGIZING BUS 2, SECT. 3 THROUGH TWO OPEN PCB'S WITH .005 μF CAPACITANCE ON EACH PHASE

BEST DOCUMENT AVAILABLE

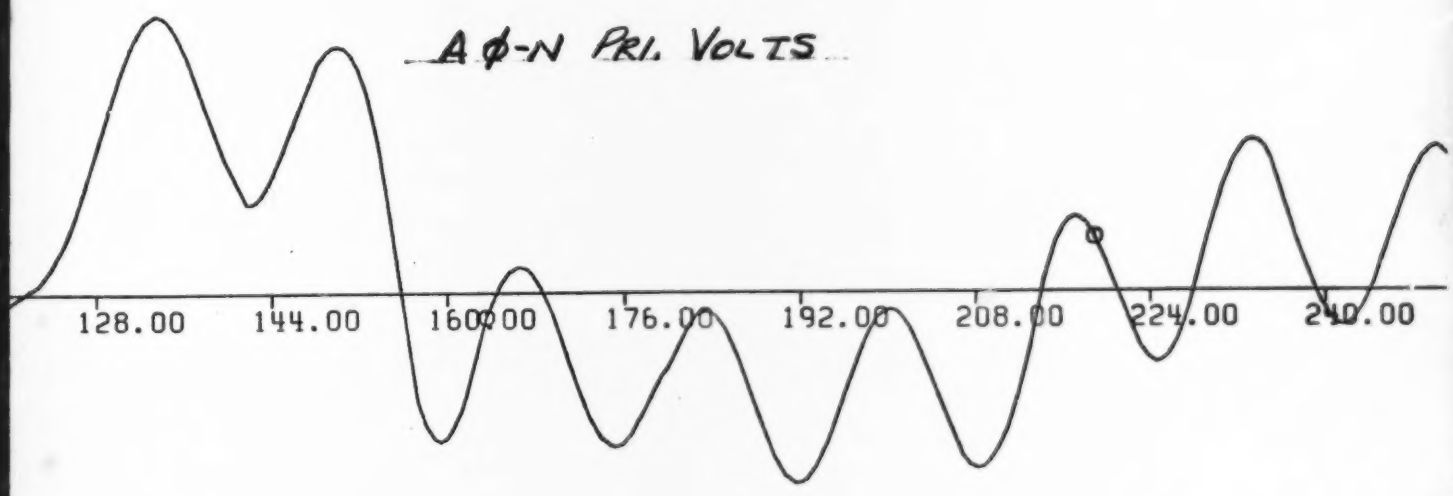


FIGURE 14B

(FIGURE 14A CONTINUED)